



NASA Conference Publication 10185

10P
61062
235086

Proceedings of the 4th Annual Workshop: Advances in Smart Materials for Aerospace Applications

Edited by
Robin C. Hardy and Joycelyn O. Simpson
Langley Research Center • Hampton, Virginia

Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration,
Washington, D.C., and held at
Langley Research Center, Hampton, Virginia
May 4-5, 1995

March 1996

Preface

In the last decade there has been tremendous progress in the sciences and technologies associated with active control. Advancements in high performance smart materials development, understanding material constitutive behavior, applied mathematics with improved models and control systems, and the development of composite manufacturing techniques have each supplied essential building blocks necessary for the conception and refinement of intelligent material systems.

The primary objective of the Fourth Annual Conference on Advances in Smart Materials for Aerospace Applications was to provide a forum for technical dialogue on numerous topics in the area of smart materials. Specifically, we wanted to examine the current state of technology in the areas of shape memory alloys, ferroelectrics, fiber optics, finite element simulation, and active control as it applies to NASA Langley programs. The papers and summaries presented herein collectively represent the diversity of the perspectives and talents which have led to the advances we have made as a technical community across the United States. The workshop hosted approximately 90 researchers from industry and the academic community along with approximately 80 attendees from NASA Langley.

The organizers of this year's conference gratefully acknowledge sponsorship by the Active Structures Technical Committee under the leadership of Dr. Garnett Horner. The organizational skills and professionalism of Pamela Verniel and her staff is sincerely acknowledged and appreciated and without which this conference could not have taken place. The dedication of the session chairpersons, including Dr. Lucas Horta, Anna McGowan, and Leland Melvin greatly furthered the success of this year's conference.

R.C. Hardy
J.O. Simpson
Hampton, VA

Page intentionally left blank

4th Annual Workshop: Advances in Smart Materials for Aerospace Applications

Government Perspectives and Applications of Smart Materials

Multifunctional Structures: The Future of Spacecraft Design , M. W. Obal, BMDO/TRC Pentagon	3 ⁻⁰
Smart Materials and Structures Applications at NASA LaRC , G. Horner, NASA Langley Research Center	31 ⁻¹
Smart Materials Research at NRL , P. Matic, NRL	47 ⁻²
Smart Materials: The Structures Division Program at Wright Laboratory , K. Demoret, WPAFB	87 ⁻⁰
The ONR Smart Materials Program , R. Barsoum, ONR	107 ⁻⁰
The ARPA Smart Materials and Structures Program , C. R. Crowe, ARPA	141 ⁻⁰

Vibration/Noise Control

Use of Smart Structures for Control and Performance Improvement of Hypersonic Vehicles , J.A. August and S.P. Joshi, University of Texas at Arlington	182 ⁻³
Electrorheological Fluids for Development of Vibration Isolation Mounts , A. Eftekhari, D.S. Parmar, and J. Singh, Hampton University and NASA Langley Research Center	187 ⁻⁴
The Piezoelectric Aeroelastic Response Tailoring Investigation: A Status Report , A. McGowan, NASA Langley Research Center	191 ⁻⁵
Control of Thermal Deflection, Panel Flutter, and Sonic Fatigue at Elevated Temperatures Using Shape Memory Alloys , C. Mei and J.K. Huang, Old Dominion University	197 ⁻⁶
Active and Passive Damping of Vibration for Rotorcraft Applications , N.W. Wereley, University of Maryland	203 ⁻⁷
Active Control of Noise Using Actuator/Sensor Arrays , D.K. Lindner and P. Winder, Virginia Tech, G. Kirby, Naval Research Laboratory	207 ⁻⁸
Aircraft Interior Noise Control Using Distributed Piezoelectric Actuators , J.Q. Sun, University of Delaware	211 ⁻⁹
Noise Reduction in an Aircraft Fuselage Model Using Active Trim Panels , K. Lyle and R. Silcox, NASA Langley Research Center	215 ⁻¹⁰
Structural Acoustic Response of Shape Memory Alloy Hybrid Composite Panels , T. Turner, NASA Langley Research Center	219 ⁻¹¹

SPICES and SMS Technology Developments

Design, Fabrication and Calibration of an Embedded Piezoelectric Actuator for Active Control Applications , G.H. Koopmann, G.A. Lesieutre, S. Yoshikawa, W. Chen, J.B. Fahnlne, S. Pai and B. Dershem, Pennsylvania State University	225 ⁻¹²
Manufacturing of Smart Structures Using Fiber Placement Manufacturing Processes , E. White, M.H. Thomas and J. H. Jacobs, McDonnell Douglas Aerospace	227 ⁻¹³
Performance of Integrated Fiber Optic, Piezoelectric, and Shape Memory Alloy	235 ⁻¹⁴

Actuators/Sensors in Thermoset Composites, C.M. Trottier, Fiber Materials Incorporated

Modeling of Electrostrictive Ceramic Actuators and Sensors, C.L. Hom and
N. Shankar, Martin Marietta Laboratories

237-0

Smart Material Demonstrators Based on Shape Memory Alloys and Electroceramics, 251-15
A.V. Cooke, Martin Marietta Laboratories

Performance of a Smart Vibration Isolator for Precision Spacecraft Instruments,
M.E. Regelbrugge, A. Carrier and W.C. Dickson, Lockheed Palo Alto Research Laboratories

253-76

Smart Materials

Sonopanel 1-3 Piezocomposite Panels for Active Surface Control, R. Gentilman,
L. Bowen, D. Fiore, H. Pham, and W. Servatka, Materials Systems Inc.

276-17

**Processing of Fine-Scale Piezoelectric Ceramic/Polymer Composites for Sensors
and Actuators**, A. Safari and V.F. Janas, Rutgers University

281-18

**RAINBOWS and CERAMBOWS: The Technologies of Pre-Stressed Piezo
Actuators**, G.H. Haertling, Clemson University

287-19

Piezoelectric Actuator/Sensor Technology at Rockwell, R.R. Neurgaonkar, Rockwell
International Science Center

288-50

Functional and Multifunctional Polymers: Materials for Smart Structures,
S. Arnold, L. Pratt, J. Li, M. Wuagaman and I.M. Khan, Clark Atlanta University

289-21

**Improved Damage Resistant Composite Materials Incorporating Shape
Memory Alloys**, J.S.N. Paine, Paradigm, Incorporated, C.A. Rogers, Virginia Tech

295-22

Fiber Optics

Fiber Optic Sensors for Smart Materials and Structures, H. Singh, C.C. Chang,
R. Boyer and J.S. Sirkis, University of Maryland

298-23

**High Temperature Testing with Sapphire Fiber White-Light Michaelson
Interferometers**, A. Barnes, J. Pedrazzani, R. May, K.A. Murphy, Virginia Tech, T. Tran, Fiber and
Sensor Technologies, Inc., J. Coate, Wright Laboratory

299-24

Metal-Coated Optical Fibers for High Temperature Applications, J. Zeakes,
M. Gunther and R. Claus, Fiber and Electro-Optics Research Center, A. Sarrafzadeh-khooee, J. Greene
and T. Tran, Fiber and Sensor Technologies, Inc.

305-25

Digital Fringe Counting for Intrinsic Fabry-Perot Interferometers, L. Melvin,
M. Froggatt and R. Rogowski, NASA Langley Research Center

306-26

Applications and Modeling of Smart Materials

**Layerwise Mechanics and Finite Elements for Smart Composite Structures with
Piezoelectric Actuators and Sensors**, D.A. Saravanos, P.R. Heyliger and D.A. Hopkins, NASA
Lewis Research Center

309-27

Finite Element Simulation of Smart Structures, Y.L. Cui and M. Panahandeh, Berkeley
Applied Science and Engineering, Inc.

315-28

**Development of a Higher Order Theory for Modeling Composite Laminates with
Induced Strain Actuators**, Aditi Chattaopadhyay and C.E. Seeley, Arizona State University

319-29

**On the Sensitivity of Piezoceramics and Piezopolymers in Structural Integrity
Monitoring of Large Trusses**, A.O. Abatan, M.W. Lin and E. Mintz, Clark Atlanta University

325-30

Construction of a Piezoresistive "Neural Sensor" Array, W.B. Carlson, W.A. Schulze, and S.M. Pilgrim, New York State College of Ceramics 329 -31

Shape Control of Solar Collectors Using Shape Memory Alloy Actuators, D.W. Lobitz, J.W. Grossman, J.J. Allen, T.M. Rice, Sandia National Laboratories, C. Liang, F.M. Davidson, San Diego State University 335 -32

Poster Presentations

Active Interior Noise Control Studies, J. Park, S. Veeramani, A. Sampath, B. Balachandran, and N. Wereley, University of Maryland 342 -33

Analysis of Sensory/Active Piezoelectric Composite Structures in Thermal Environments, H.J. Lee and D.A. Saravanos, NASA Lewis Research Center 347 -34

Characterization of the Dynamic Material Properties of Magnetostrictive Terfenol-D, F.T. Calkins, A.B. Flatau, D.L. Hall, Iowa State University 353 -35

Constitutive Models for Shape Memory Alloy Polycrystals, R.J. Cornstock, M. Somerday and J.A. Wert, University of Virginia 357 -36

Design of a Mode Conversion Ultrasonic Motor for Position Control, R. LeLetty, F. Claeysen, N. Lhermet, Cedrat Recherche, and P. Bouchilloux, Magsoft Corporation 361 -37

Detection of Delamination in Composite Beams Using Broad Band Acoustic Emission Signature, A.C. Okafor, K. Chandrashekhara, Y.P. Jiang, University of Missouri-Rolla 363 -38

Development of High Performance Piezoelectric Polymers, J.O. Simpson and T.L. St.Clair, NASA Langley Research Center 368 -39

Development of Torsional and Linear Piezoelectrically Driven Motors, K. Duong, D. Newton and E. Garcia, Vanderbilt University 373 -40

Effect of Temperature and Deformation Rate on the Tensile Mechanical Properties of Polyimide Films, S.R. Moghazy and K.C. McNair, Clark Atlanta University 374 -41

Electromechanical Materials for Cryogenic Use, P. Leldinger and S.M. Pilgrim, New York State College of Ceramics 375 -42

First Cycle Heterogeneous Deformation Behavior and Cyclic Shakedown Phenomena of Nitinol Near A_f Temperatures, H.N. Jones, Naval Research Laboratory 381 -43

Incorporation of a New Benzofulvene Derivative into Polymers to Give New NLO Materials, A.D. Bowens, X. Bu, E.A. Mintz, Clark Atlanta University, Y. Zhang, Laser Photonics Technology, Inc. 386 -44

Metal-Coated Optical Fibers for High Temperature Applications, J. Zeakes, M. Gunther and R. Claus, Fiber and Electro-Optics Research Center, A. Sarrafzadeh-khoei, J. Greene, T. Tran, and K. Murphy, Fiber and Sensor Technologies, Inc. 388 -46

Piezoelectric Actuator and Sensor Design for Nonlinear Panel Flutter Suppression, J.K. Huang and C. Mei, Old Dominion University 389 -47

Real Time Digital Control of Magnetostrictive Actuators, R.L. Zrostlik, D.L. Hall, A.B. Flatau, Iowa State University 393 -47

The Piezoelectric Aeroelastic Response Tailoring Investigation, A. McGowan, NASA Langley Research Center 191 -3

Variable Geometry Truss, G. Horner, NASA Langley Research Center 397 -48

Government Perspectives and Applications of Smart Materials

Chairperson: Dr. Garnett Horner

Page intentionally left blank

**Multifunctional Structures
4th Annual Advances in Smart Materials for
Aerospace Applications Workshop**

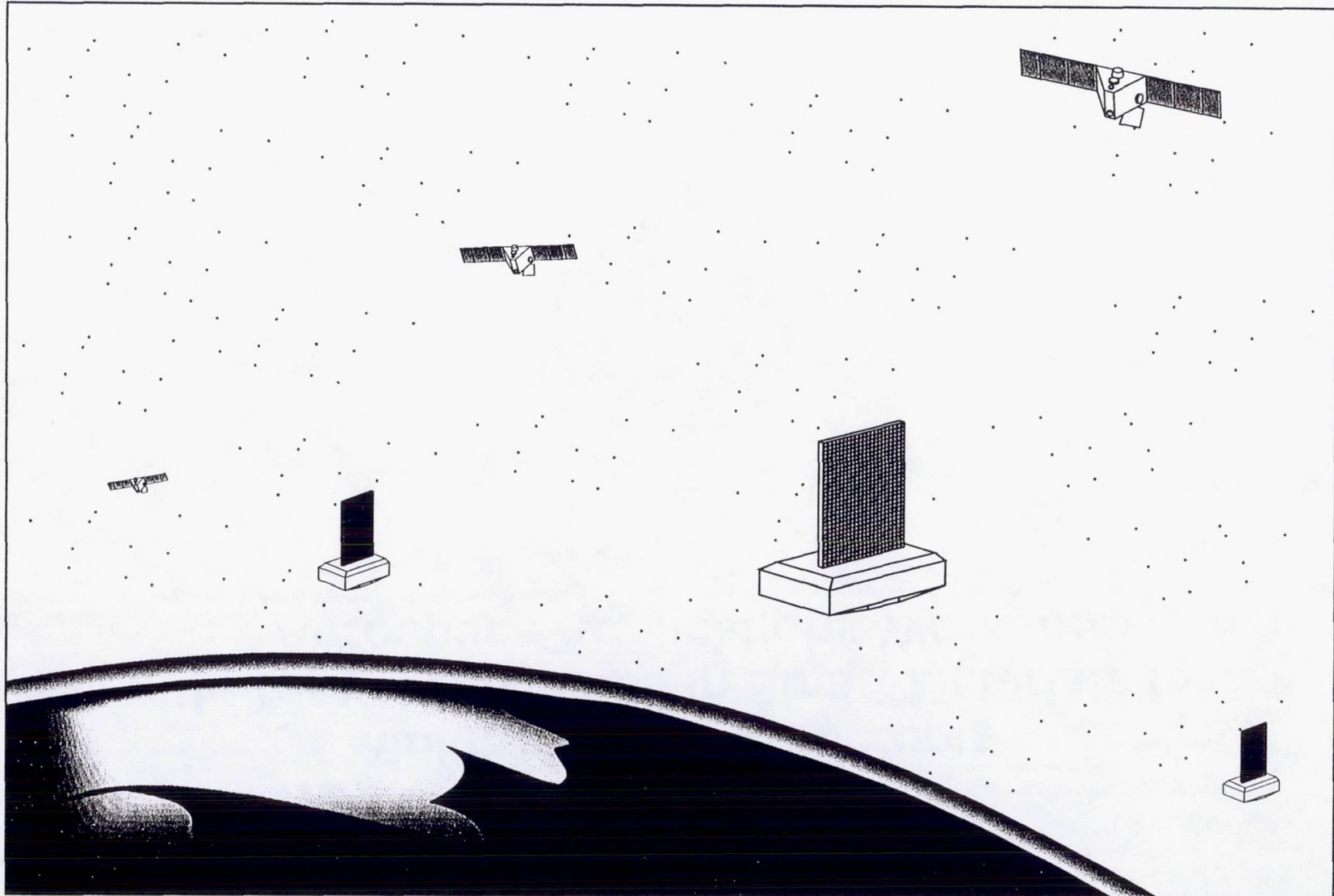


**Dr. Michael Obal, Lt Col USAF
May 4-5, 1995**

MIT



Defense Satellite Constellations





Defense Satellite Constellation Costs

- To reduce cost of a defense satellite constellation
 - Design each element for minimum mass → launch costs
 - Design each element to be autonomous → constellation management control costs

Examples:

- Autonomous navigation for deployment and station keeping
- Autonomous system on orbit health monitoring for natural and threat environments
- Autonomous satellites require reliable sensors, processors, health monitoring subsystems and power all of which adds mass that increases launch costs (Catch-22).

Multifunctional structures offer a potential solution

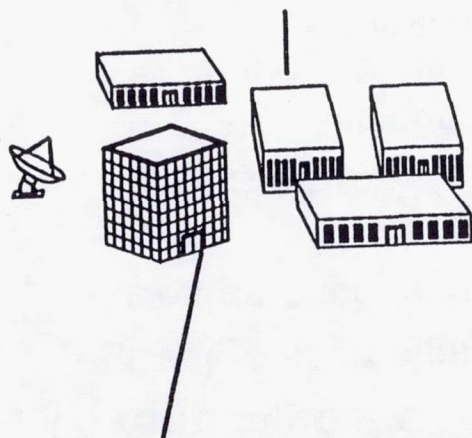


Ground/Launch Risks

Ground

Ground System Complexity S/W-Human-H/W I/F

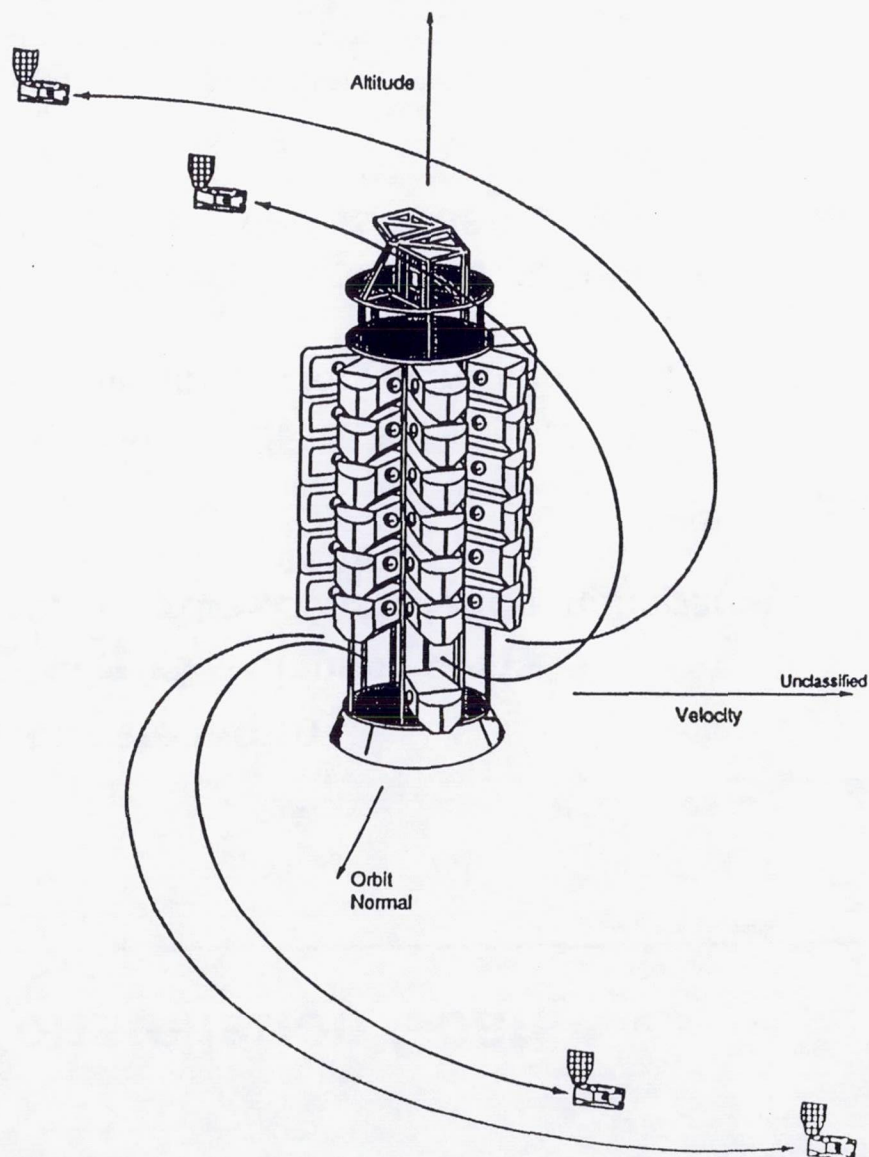
- Complexity of software to be developed
- New technology
- Ops concept/autonomy
- Productivity rates



Large Scale S/W Development/Ground/Quantity

- Quantity of software to be developed
- Requirements changes/uncertainties
- Productivity Rates
- Verification/Validation

Launch



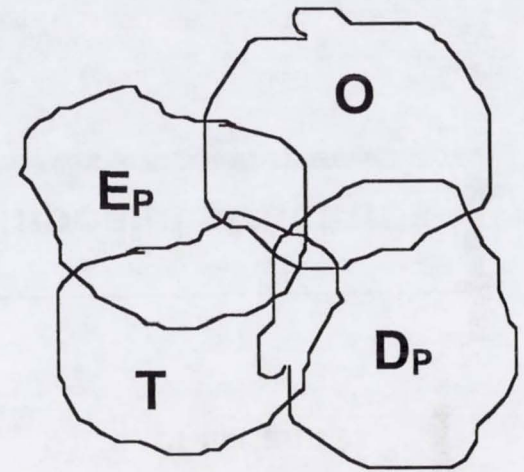
Multi-Functional Structures: Definitions

Let H be the union of the following sets

$$H = T \cup D_P \cup E_P \cup O$$

where $x \in H$

$$H = \{ x | x \in T, x \in D_P, x \in E_P, x \in O, \text{ or } x \in T \cap D_P \cap E_P \cap O \}$$



(1)

Where the set

$\{T\} \equiv$ Materials configured to manage thermal loads

$\{D_P\} \equiv$ Materials that enhance structural passive damping

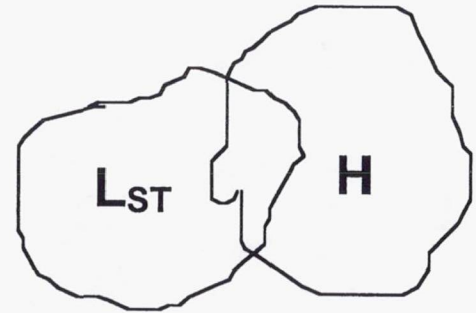
$\{E_P\} \equiv$ Passive electronic materials and circuits (shielding, ground planes, waveguides)

$\{O\} \equiv$ Other specialty materials or electronic devices

Multi-Functional Structures: Definitions

Type O Multi-functional Structures

$$M_O = L_{ST} \cap H$$



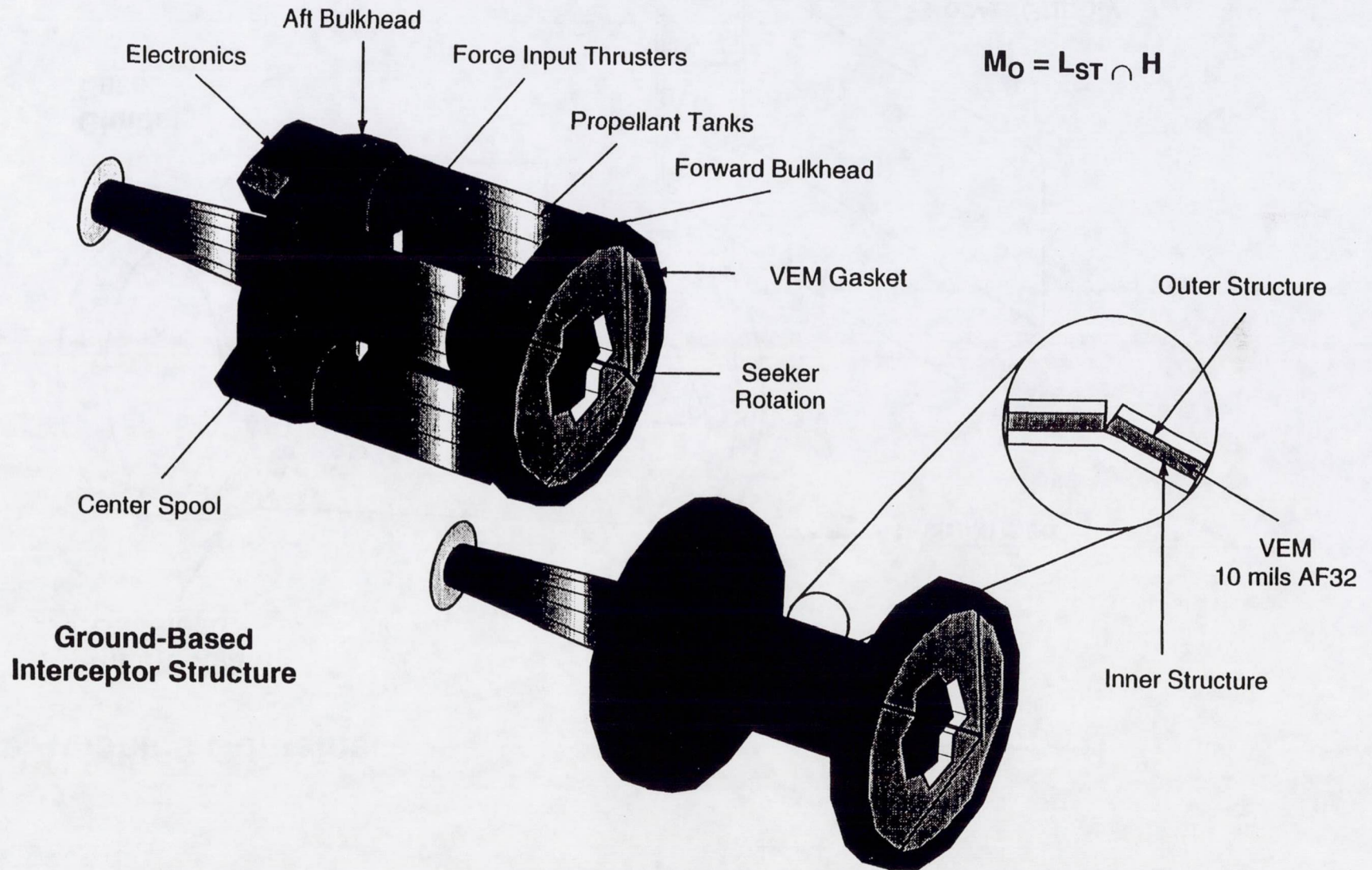
Where

∞ $\{L_{ST}\} \equiv$ Materials configured to carry structural loads

Intersection of the set
of L_{ST} and H

The most common application of advanced composite structures

Advanced Type O Multi-Functional Structure Application

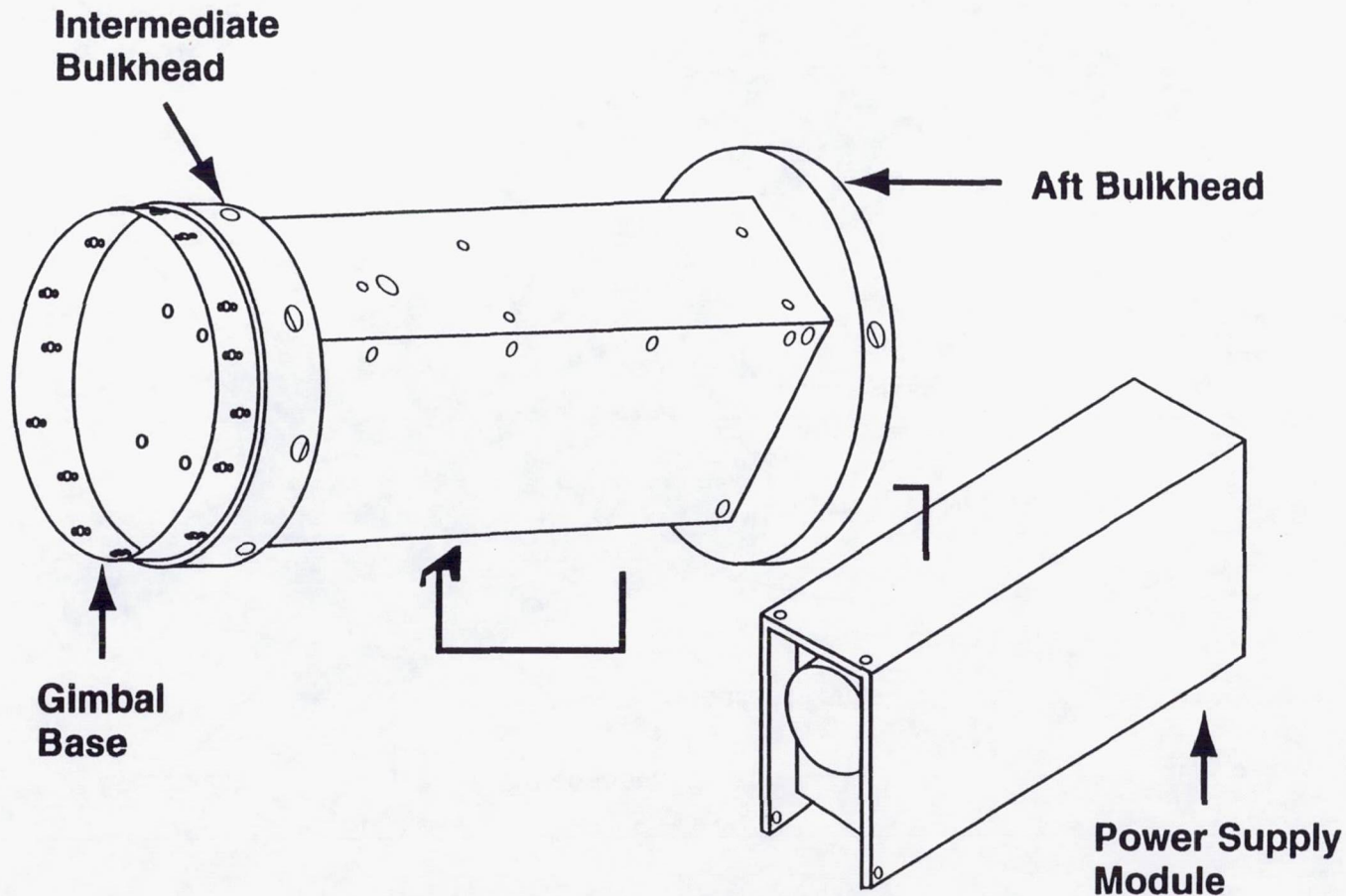


Load-Bearing Composite with High Stiffness and Passive Damping for Jitter Control

Advanced Type O Multi-Functional Structure Application

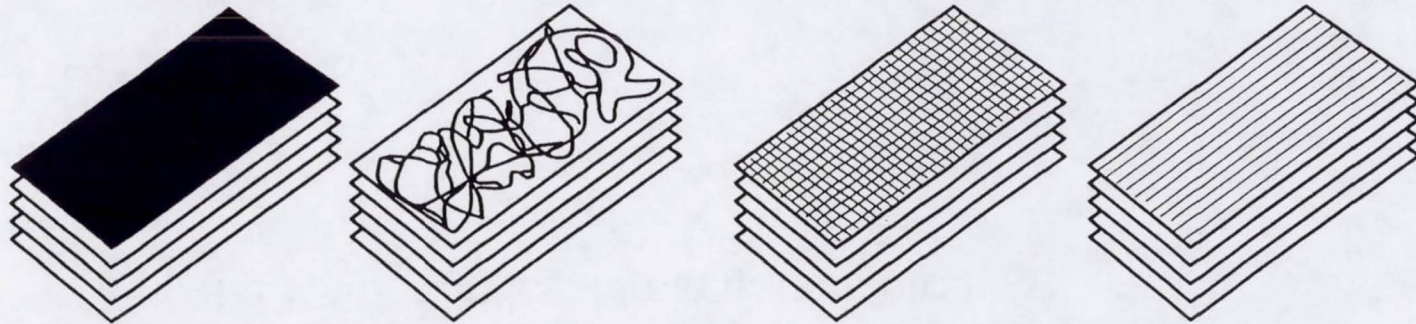
Missile Avionics Container

$$M_O = L_{ST} \cap H$$



Load-Bearing Composite with Thermal Control, EMI, and Ground-Plane Shielding

Approaches for Composite Electronic Component Packaging Structures



	METAL SHEET SPUTTER COATING PLATING SURFACE MESH (APPLY) SECONDARILY)	RANDOM NICKEL- COATED GRAPHITE FIBER MAT (NON-WOVEN) (MOLDED-IN)	NICKEL-COATED GRAPHITE FIBER CLOTH (WOVEN) (MOLDED-IN)	CO-WOVEN METAL FILAMENT (MOLDED-IN)
EMI SHIELDING	GOOD	GOOD	EXCELLENT FOR FLAT SHAPES	MINIMAL
GROUND PLANE	EXCELLENT	MINIMAL	GOOD	GOOD

Multi-Functional Structures: Definitions

Advanced Applications of M_O Type Multi-functional Structures Involving the Integration of Sensors

- **Sensory Structures L_{SES}**

Simple form

$$L_{SES} = L_{ST} \cap D_S$$

Where

$\{L_{ST}\} \equiv$ Materials configured to carry structural loads

$\{D_S\} \equiv$ Sensor and associated signal and power connectors
(PZT, fiber optics, strain gages, etc.)

More likely form

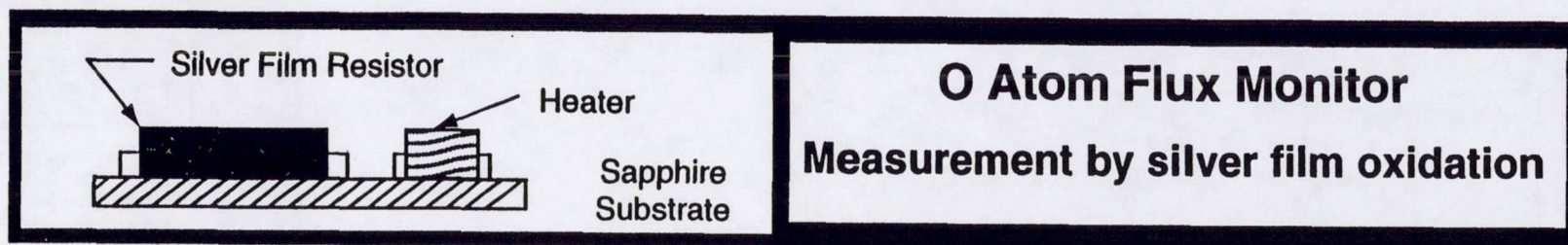
$$L_{SES} = M_O \cap D_S$$

Where

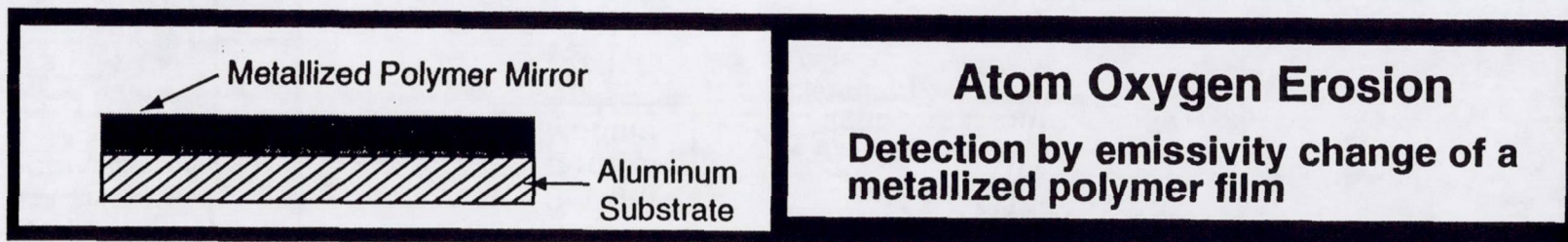
$\{M_O\} \equiv$ Type O multi-functional structures

SAMMES Applications

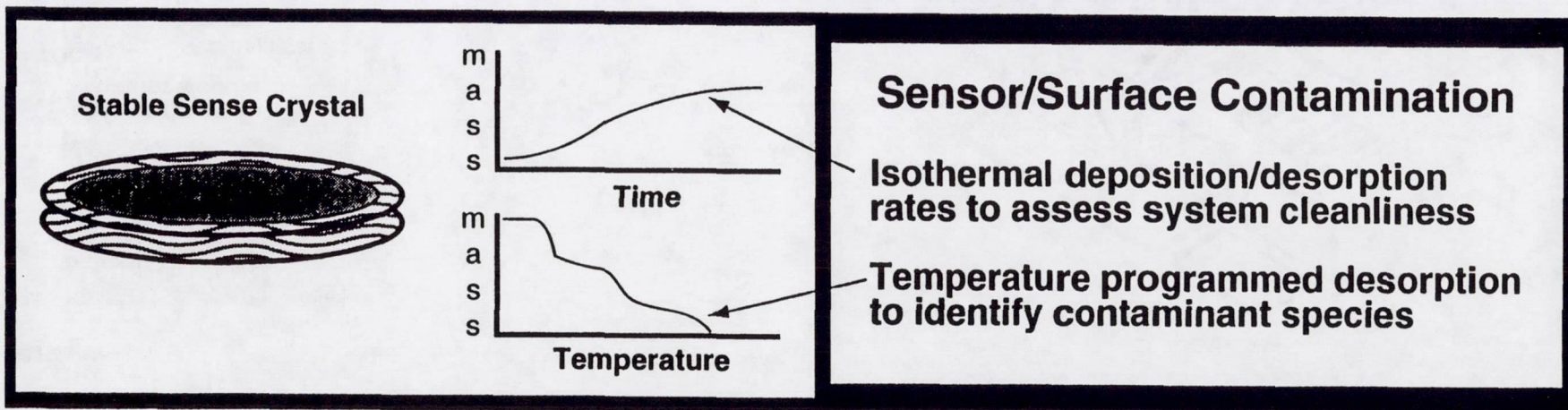
Actinometer



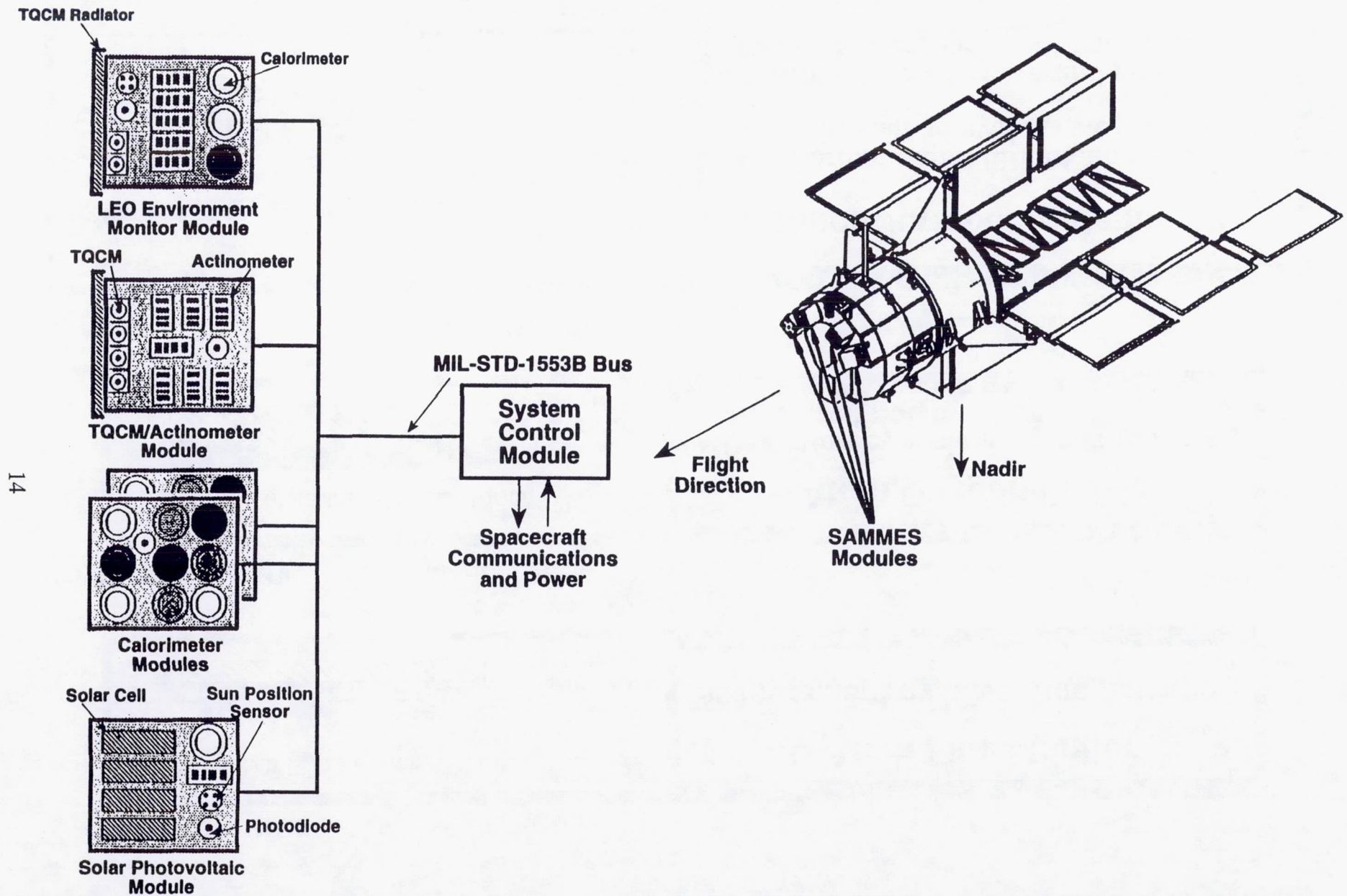
Calorimeter



QCM

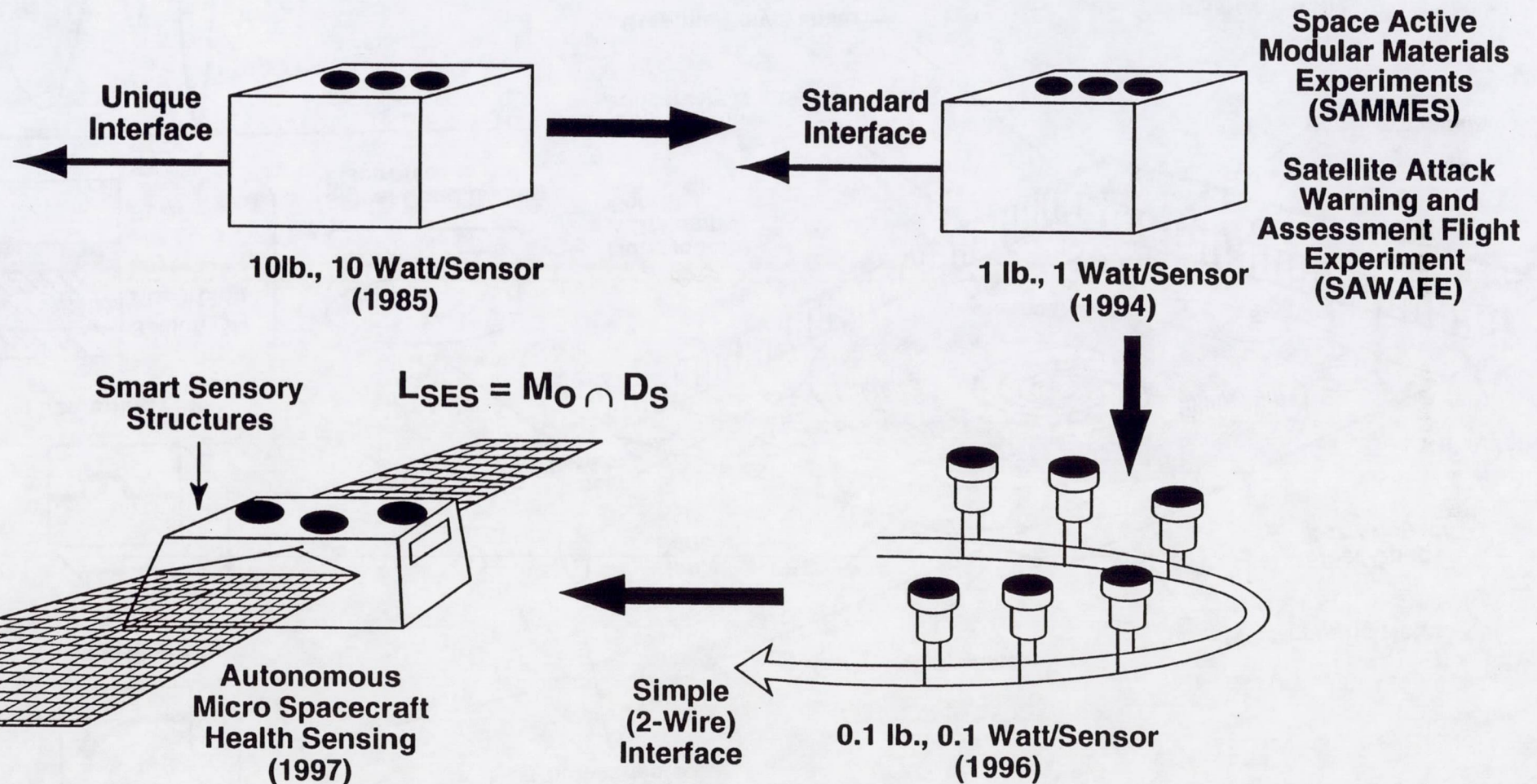


Deployed Configuration of the SAMMES Modules on STEP-3



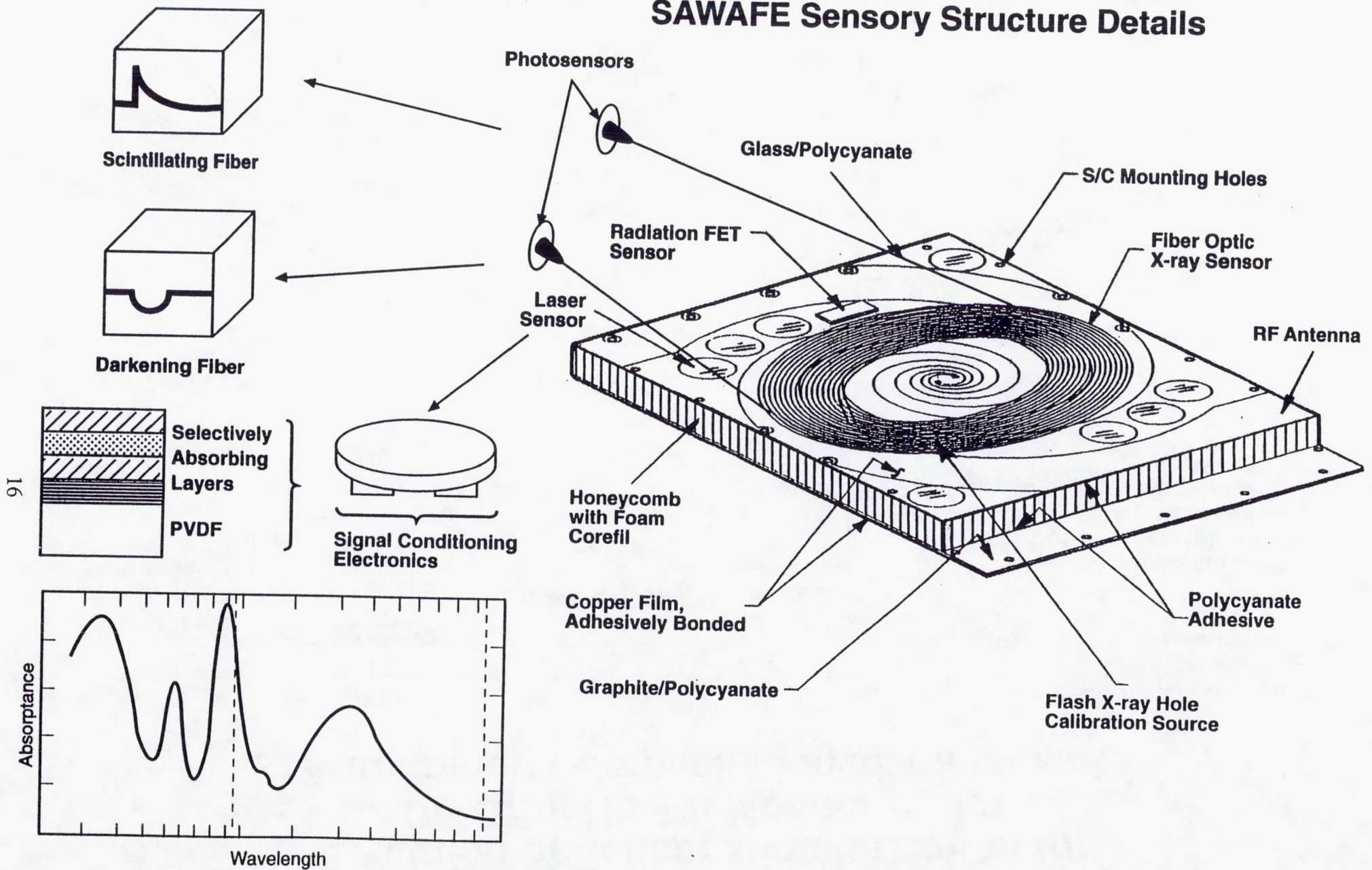
14

Evolution of Sensor Miniaturization for On-Orbit Health Monitoring for Autonomous Constellation Management



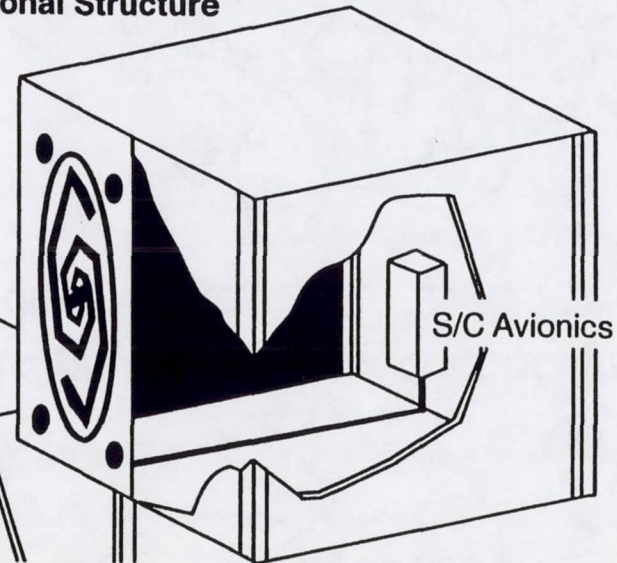
Sensor Miniaturization for Development of Sensory, Adaptive, Type I, and Type II Multi-Functional Structures

SAWAFE Sensory Structure Details

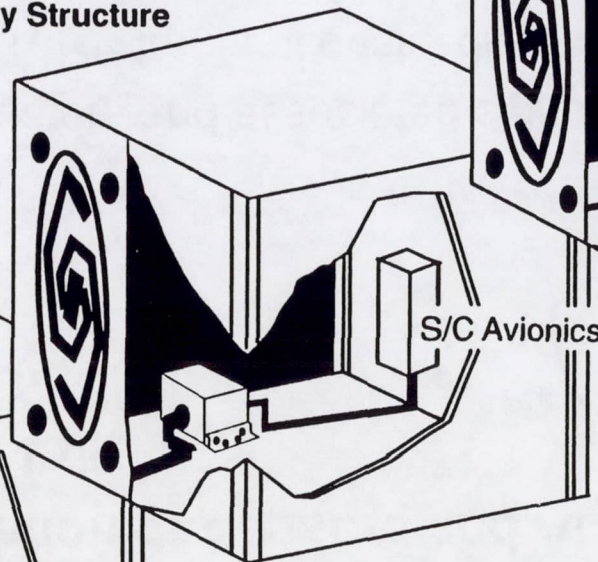


Multi-Functional Structures Payload Technology Evolution

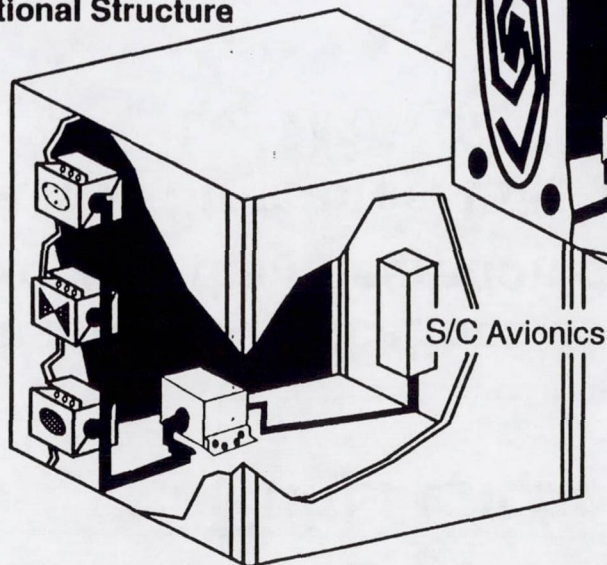
Type I or II Multi-Functional Structure



Type O Multi-Functional Sensory Structure



Type O Multi-Functional Structure



Sensors, A/D, and Processor Integrated into a Panel Providing:

- Load-bearing capability
- Thermal control
- Radiation & EMI shielding (SAWAFE 2)

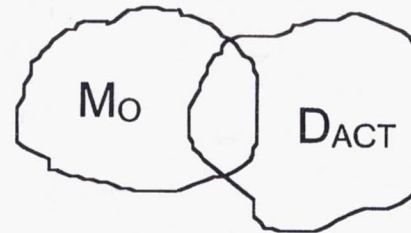
Sensors and A/D Integrated into a Panel (SAWAFE 1)

Multi-Functional Structures: Definitions

Advanced Applications of M_O Type Multi-functional Structures Involving the Integration of Sensors and Actuators

- **Active Structures** L_{ACS}

$$L_{ACS} = M_O \cap D_{ACT}$$

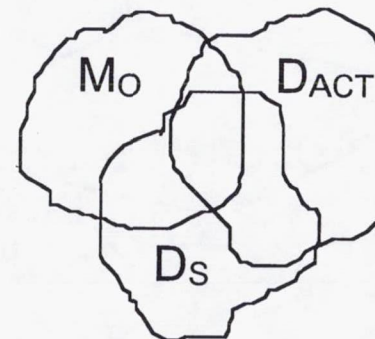


Where

$\{D_{ACT}\} \equiv$ Actuators and associated signal and power connectors
(PZT, RF trans, acoustic drivers, etc.)

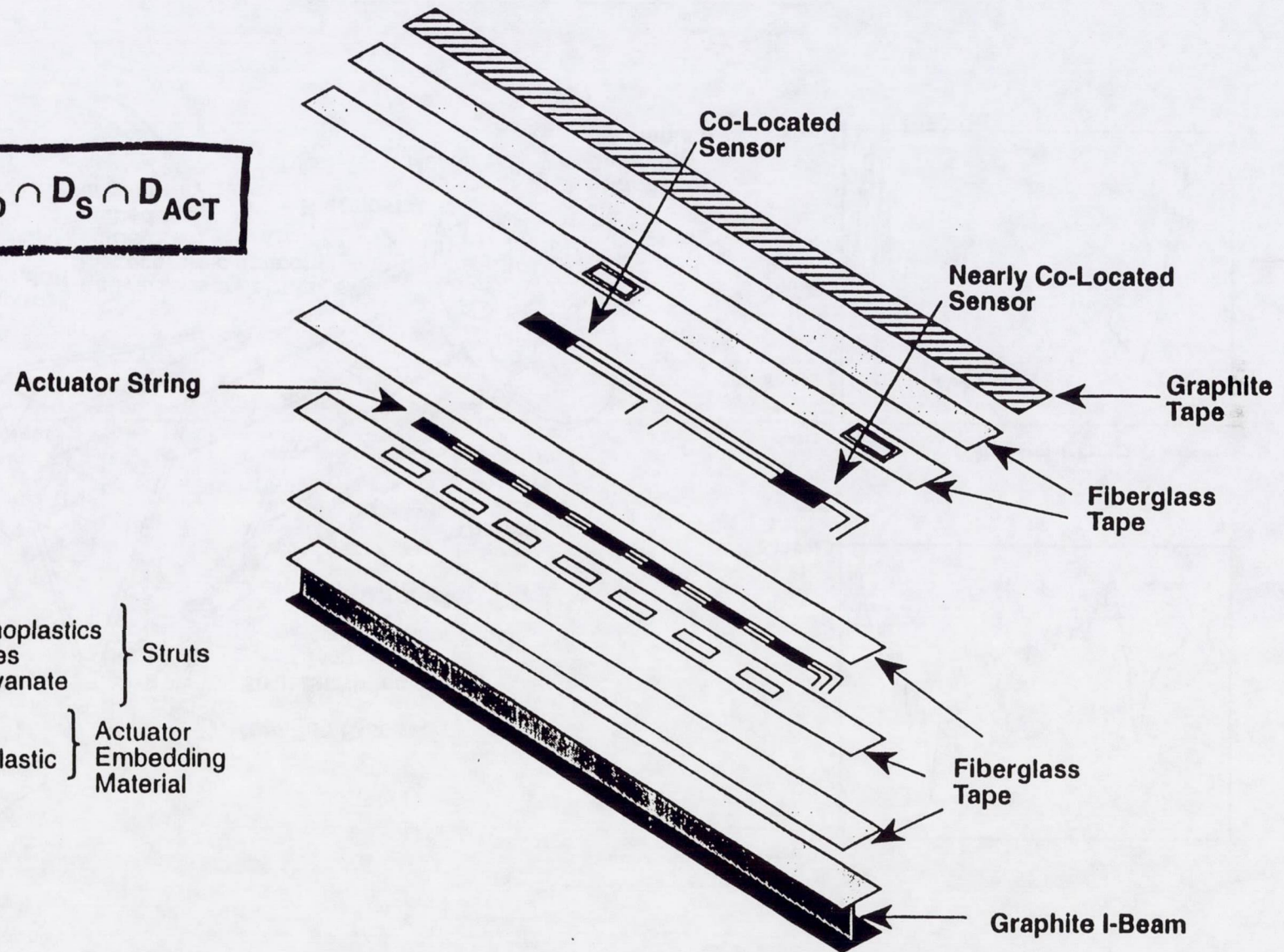
- **Adaptive Structures** L_{ADS}

$$L_{ADS} = M_O \cap D_S \cap D_{ACT}$$



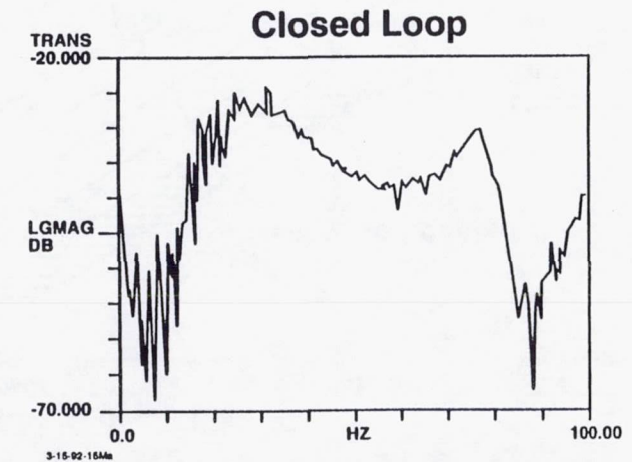
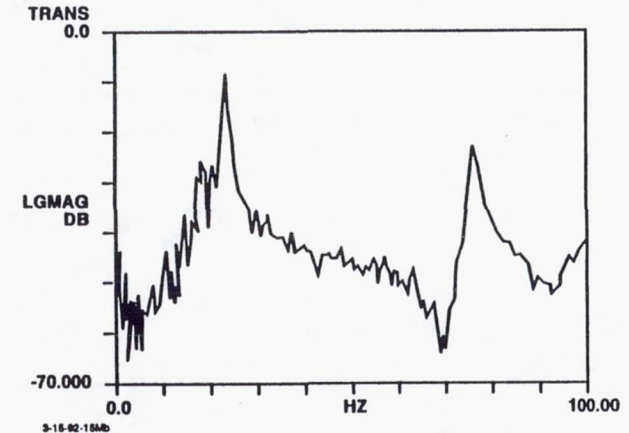
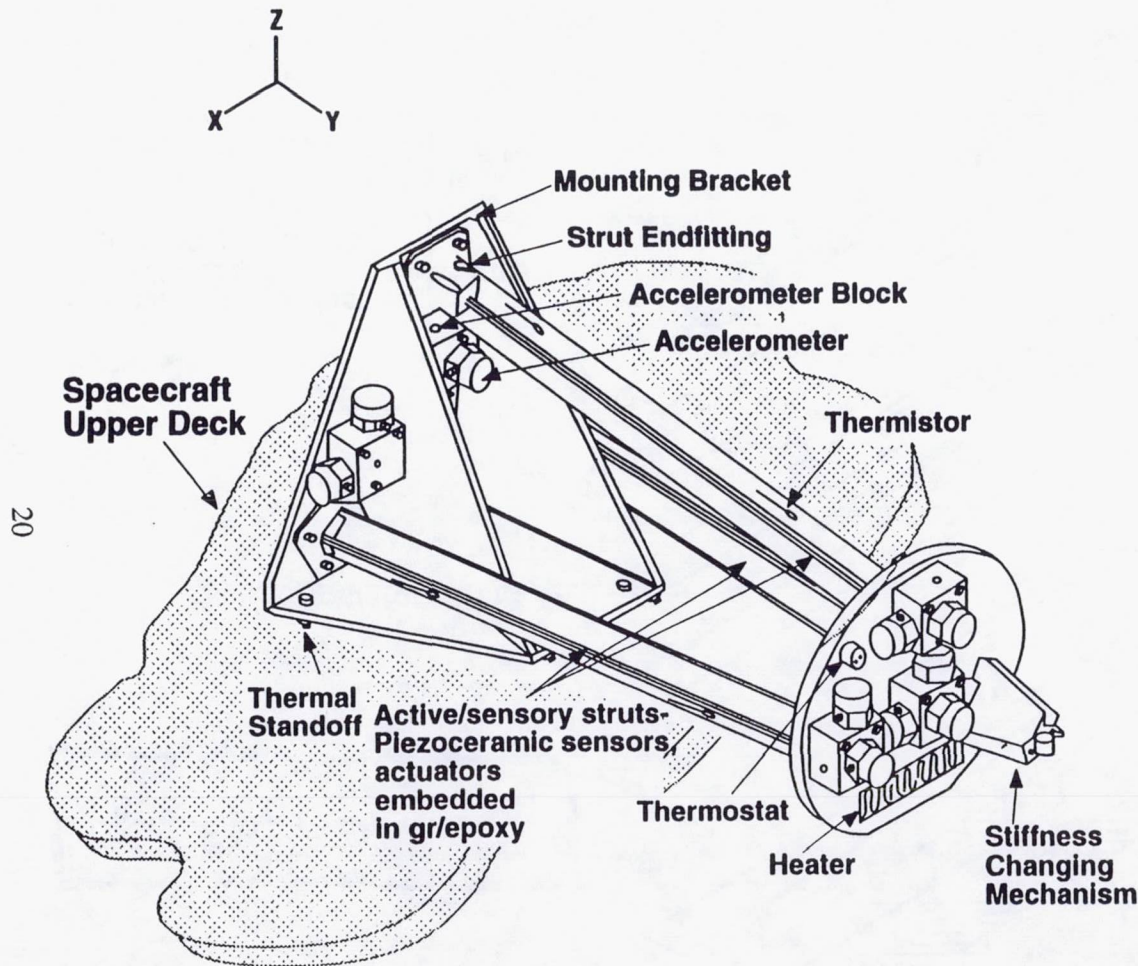
Fabrication of Adaptive Structures

$$L_{ADS} = M_O \cap D_S \cap D_{ACT}$$



Type O Multi-Functional Structure (M_O) With Integrated Sensors and Actuators

Adaptive Structures Space Experiment Advanced Control Technology Experiment I



Adaptive Structures Providing Jitter Control

Multi-Functional Structures: Definitions

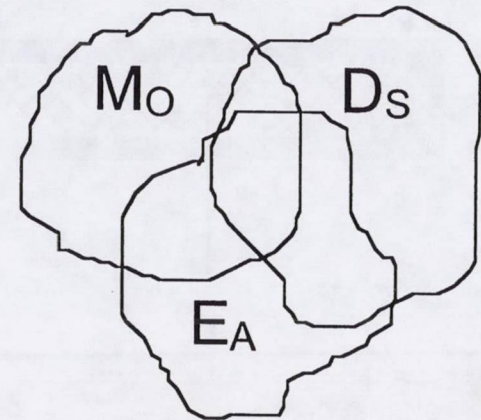
- **Type I Structure**

$$M_I = M_O \cap D_S \cap E_A$$

where

$E_A \equiv$ Active processing electronics

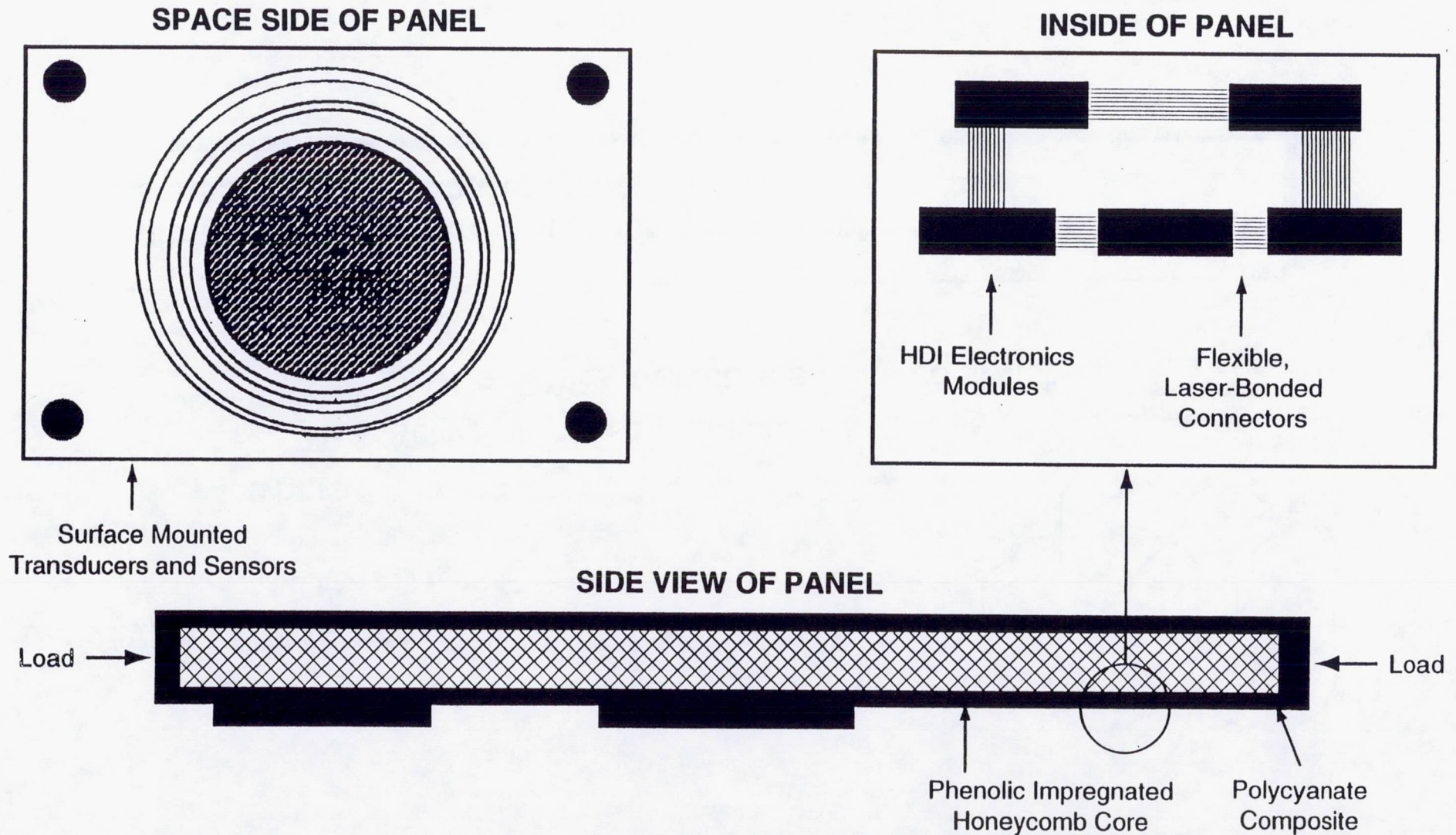
(ADCs, DSPs, transformers, micro switches)



Multi-functional structures integrating active electronics with sensors integral to the structure

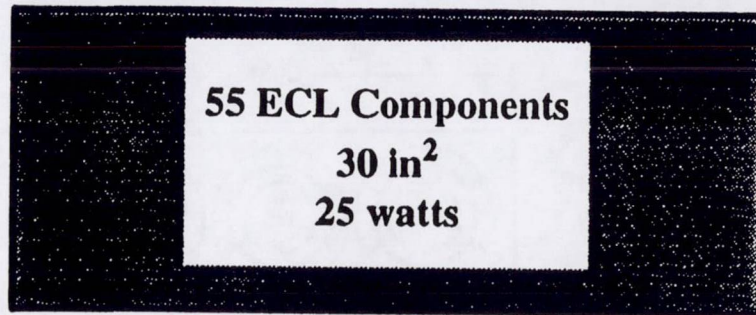
Type I Multi-Functional Structure Example

Satellite Attack Warning and Assessment Flight Experiment 2 (SAWAFE-2)

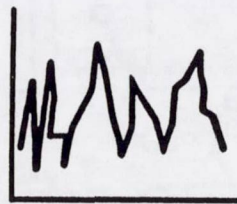


Active Electronics (E_A) Integrated Into a Sensory Structure

SATELLITE TECHNOLOGY DEVELOPMENT HIGH SPEED GaAs APPLICATION SPECIFIC INTEGRATED CIRCUIT



1 GaAs
ASIC
1.5 in²



50 samples x 8 bits
every
500 nsec

ASIC

> 500 MIPS
equivalent
throughput

3 peak amplitudes, 3 frequencies every 500 nsec
12 Mbytes / sec output

DESCRIPTION:

- Advanced technology for reducing component count, decreasing board area, and minimizing power in applications requiring high speed
- Single chip capable of processing information at 100's of MIPS equivalent computational throughput
- Enabling technology for autonomous instrumentation systems operating remotely in hostile environments
- Enabling technology for programs requiring fast design and production cycle for complex instrumentation systems

APPLICATION:

- Processing of high-bandwidth information to extract events and signals of interest
- High-speed peak detection and selection
- Remote, hand-held, and space instrumentation systems: FORTE, IAEA, RULLI, etc
- Critical component in threat warning system to fly on STEP3 satellite in October 1994

SPONSOR

U.S. Department of Energy

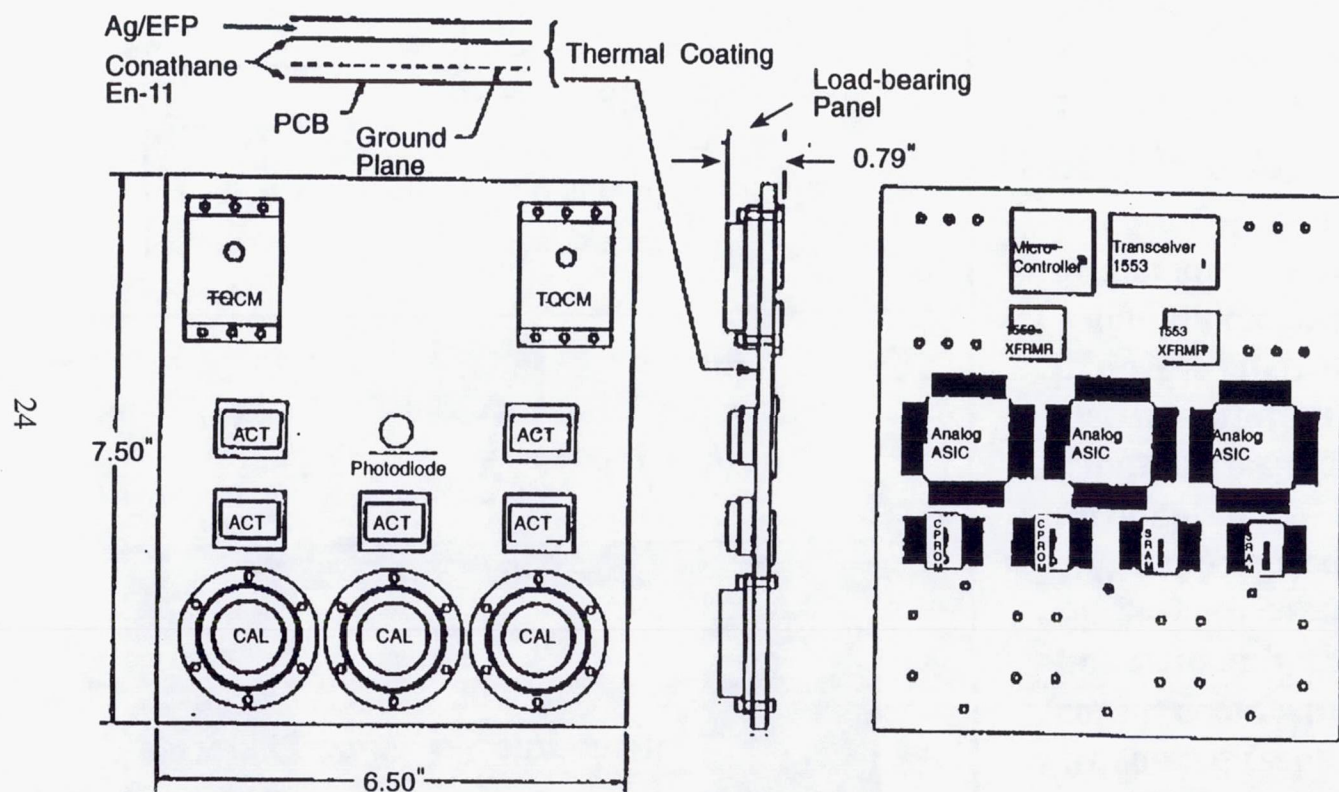
DEVELOPER:

Los Alamos National Laboratory

STO-120

Type I Multi-Functional Structure Example

Space Active Modular Materials Experiments 2 (SAMMES-2)



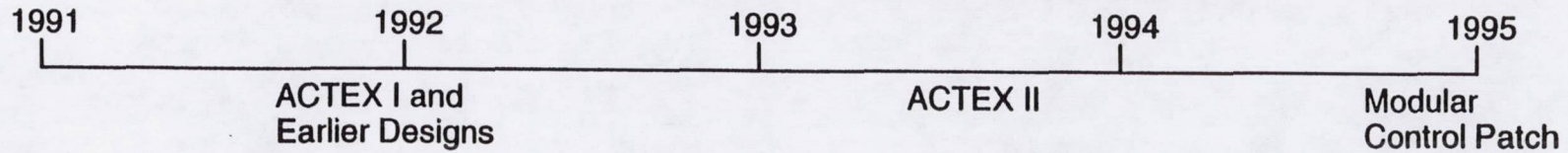
SAMMES-2 Embedded sensor electronics panel, top, side and bottom views

$$M_I = M_O \cap D_S \cap E_A$$

$$\text{or} = L_{SES} \cap E_A$$

Active Electronics (E_A) Integrated Into a Sensory Structure

Maturity Path for Multi-functional Structures Control Electronics



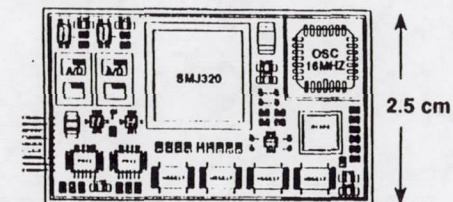
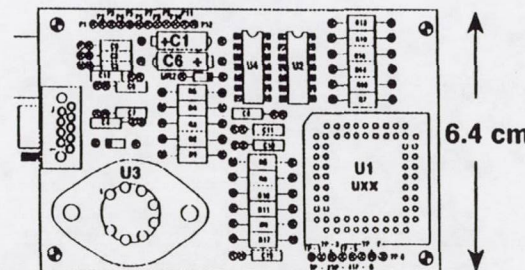
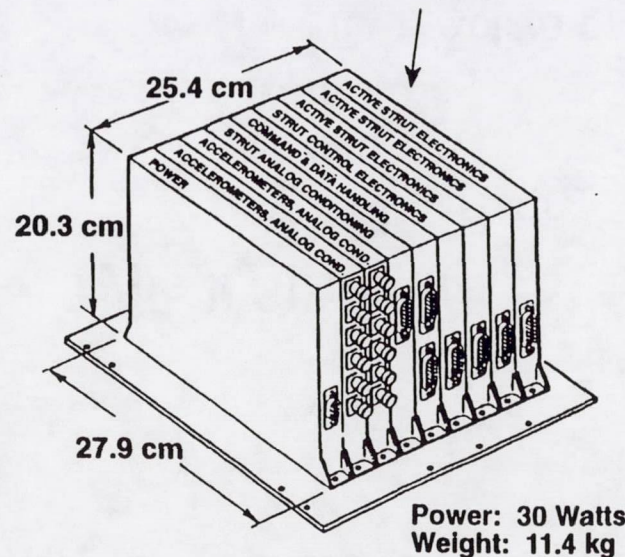
- Analog
- Controlled by On/Off
- Fixed Gains
- Breadboard

- Digital Programmable Analog Compensator
- Fixed Filters
- Controlled by RS232 Interface
- PC Board
- 15,863 cm³ Volume
- Remotely Located from Smart Structure

- Digital Compensator
- Fixed Filters
- Controlled by RS232 Interface
- PC Board
- Automatic System ID
- 156 cm³ Volume
- Local to Structure

- Digital Compensator
- Reprogrammable Filters
- High Speed Serial Interface
- Multichip Module
- Automatic System ID
- Self Thermal Control
- Over-Vibration Control
- 15.6 cm³ Volume

- Digital Compensator
- Reprogrammable Filters
- High Speed Serial Interface
- Multichip Module
- Automatic System ID
- High Bandwidth
- High Resolution
- Over-Vibration Control
- Reduced Interface Wire Count (local voltage control)
- Inputs for Accelerometers and Force Transducers



Miniaturization of Active Electronics for Development of Type I or II Multi-Functional Structures

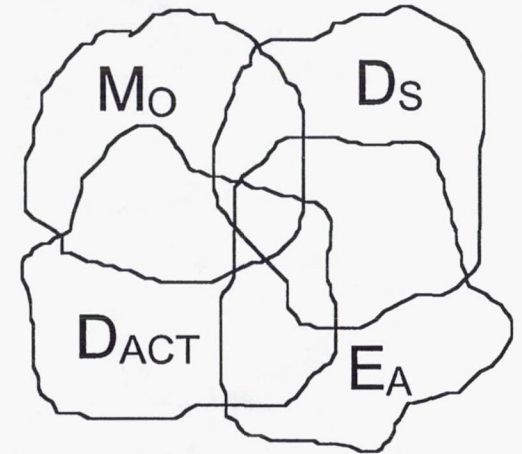
Multi-Functional Structures: Definitions

- **Type II Structure**

$$M_{II} = M_I \cap D_{ACT}$$

where

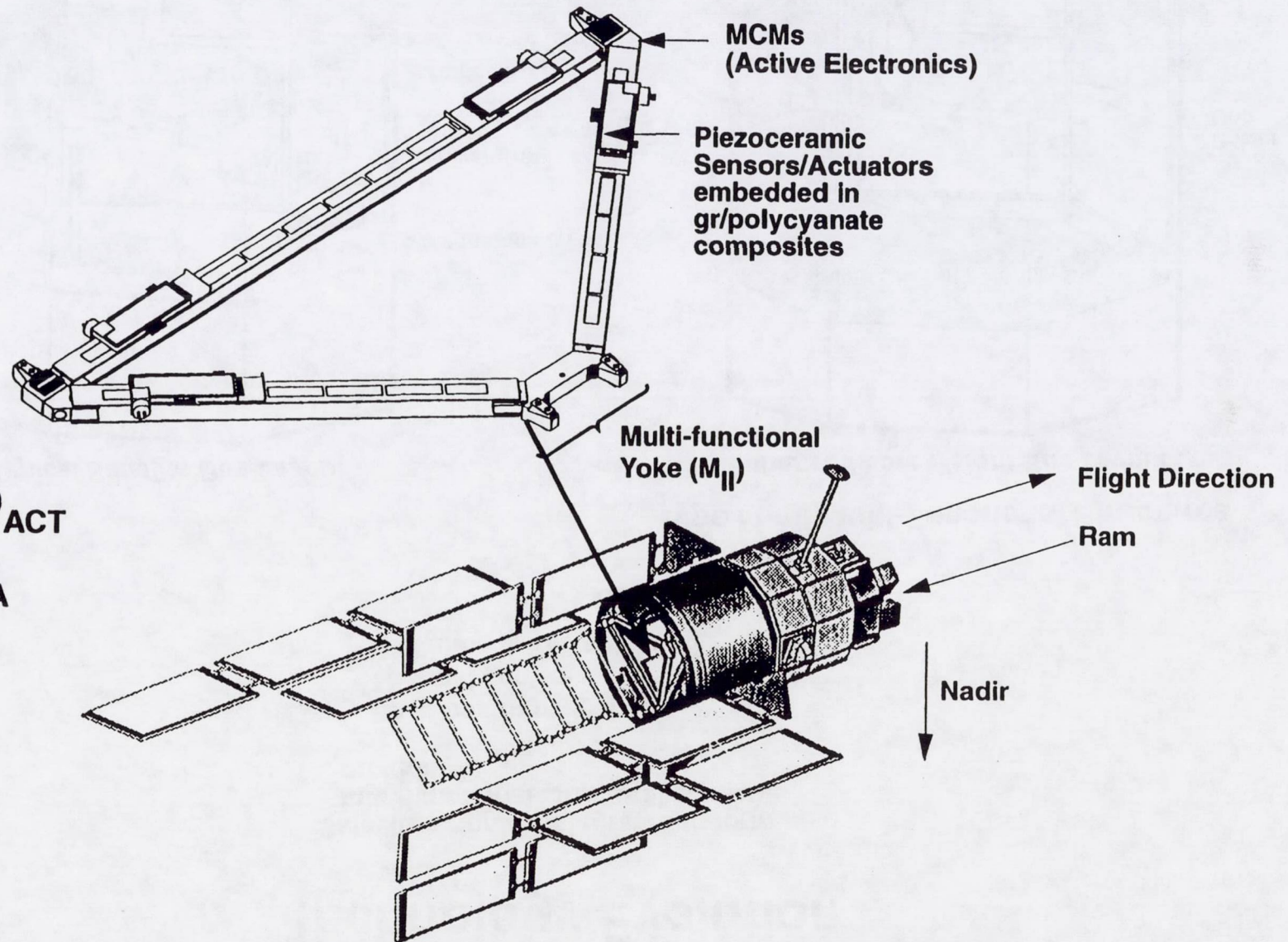
$E_A \equiv$ Active processing electronics
(ADCs, DSPs, transformers, micro switches)



Multi-functional structures integrating active electronics with sensors and actuators integral to the structure

Type II Multi-Functional Structure Example

Advanced Control Technology Experiment 2 (ACTEX-2)



$$M_{II} = M_I \cap D_{ACT}$$

$$= L_{ADS} \cap E_A$$

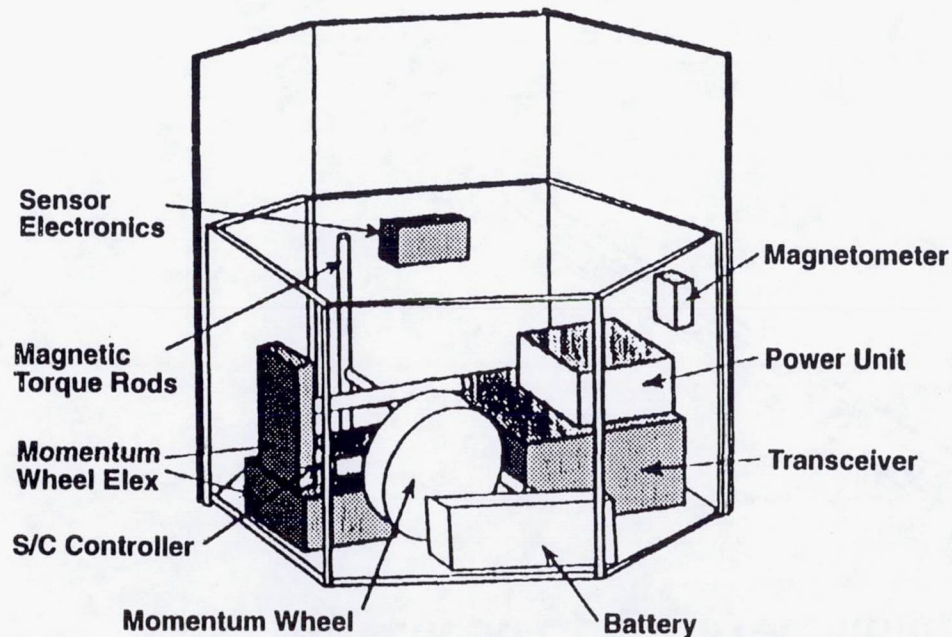
Active Electronics(E_A) Integrated Into an Adaptive Structure

Multi-Functional Structures Subsystem Technology Evolution

Satellite avionics integrated to form
multifunctional structural elements
providing:

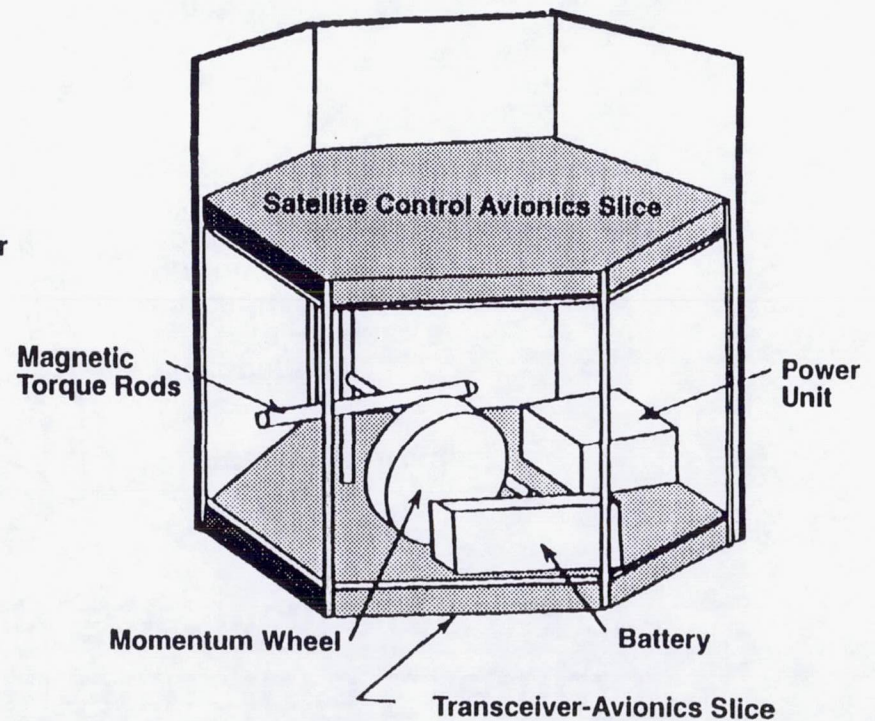
- Load-bearing capability
- Thermal control
- Radiation & EMI shielding

Typical Satellite Bus Layout



Type I or II Multi-Functional Structures

Enhanced Low Weight Bus Layout



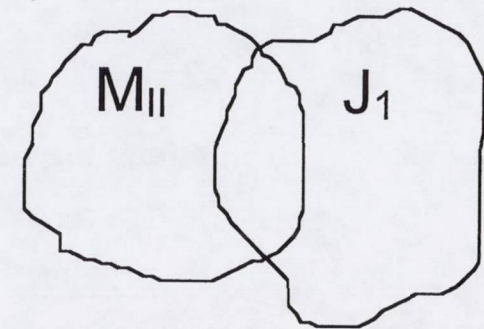
Multi-Functional Structures: Definitions

- Expansion to Higher Levels by Examples

$$M_{III} = M_{II} \cap J_1$$

where

$\{J_1\} \equiv$ higher order “intelligent” structures

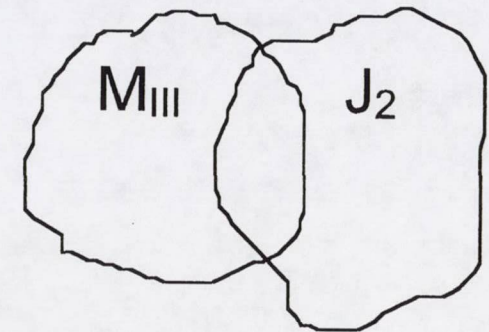


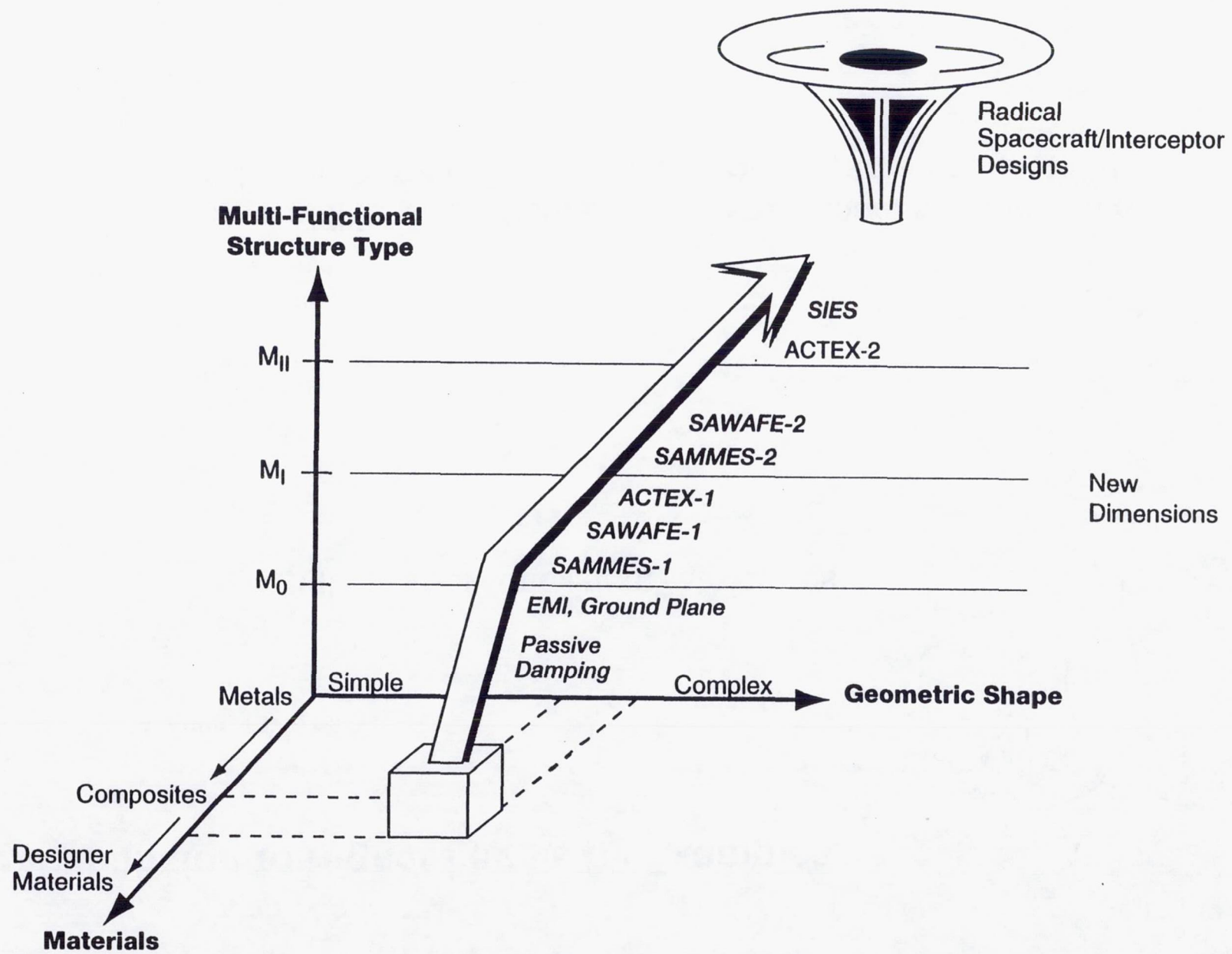
or

$$M_{IV} = M_{III} \cap J_2$$

where

$\{J_2\} \equiv$ additional configurable multi-functional structures, i.e., “cellular robot” or “CEBOT” concept [Ueyama *et al.*, 1992]





Innovative Design Options Provided by Multi-Functional Structures Concepts

Smart Materials and Structures Applications at the NASA Langley Research Center

Garnett Horner

NASA Langley Research Center
Hampton, VA

4th Annual Workshop:

Advances in Smart Materials for Aerospace Applications

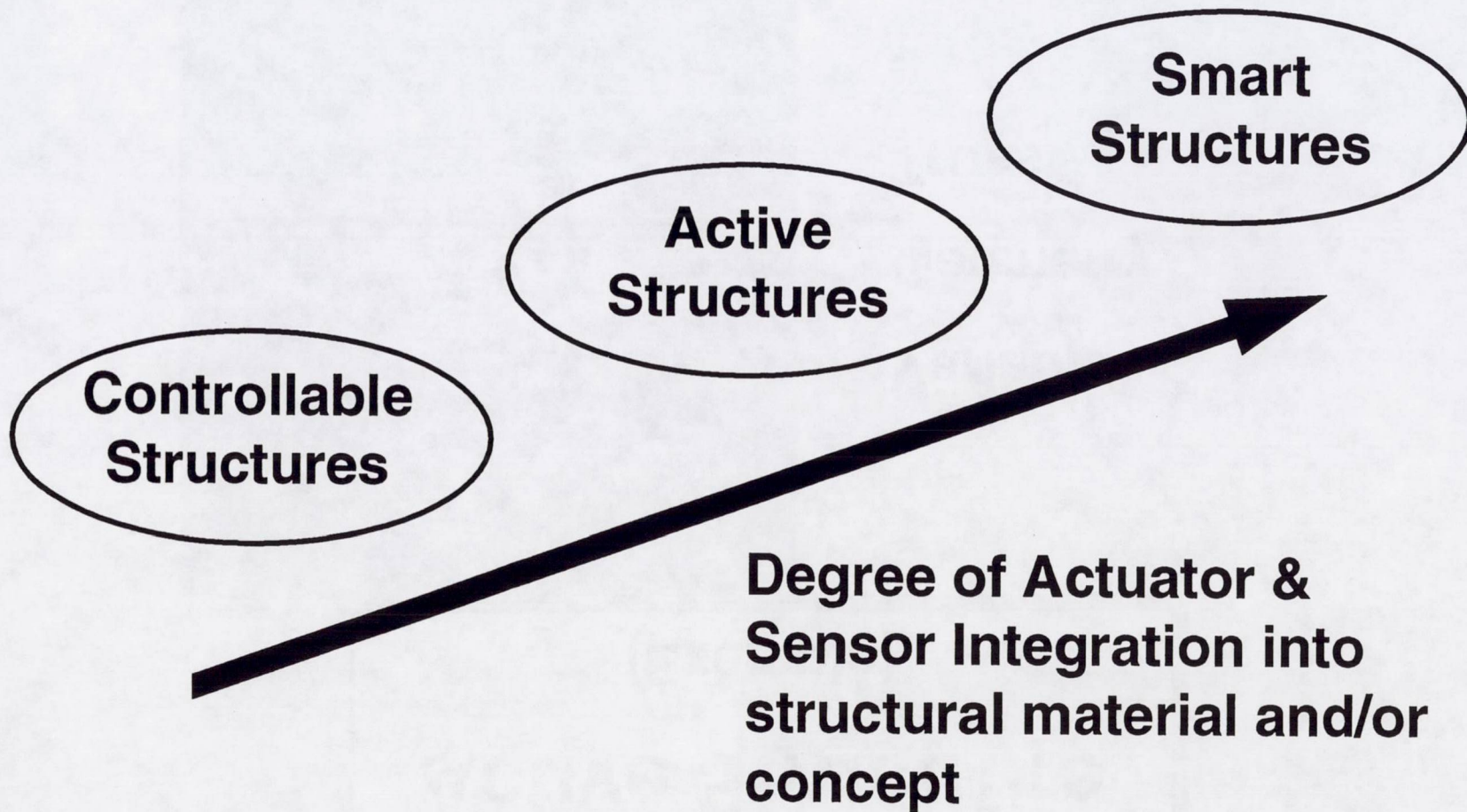
May 4, 1995

91-27
6/14/13
168.
025087

Outline

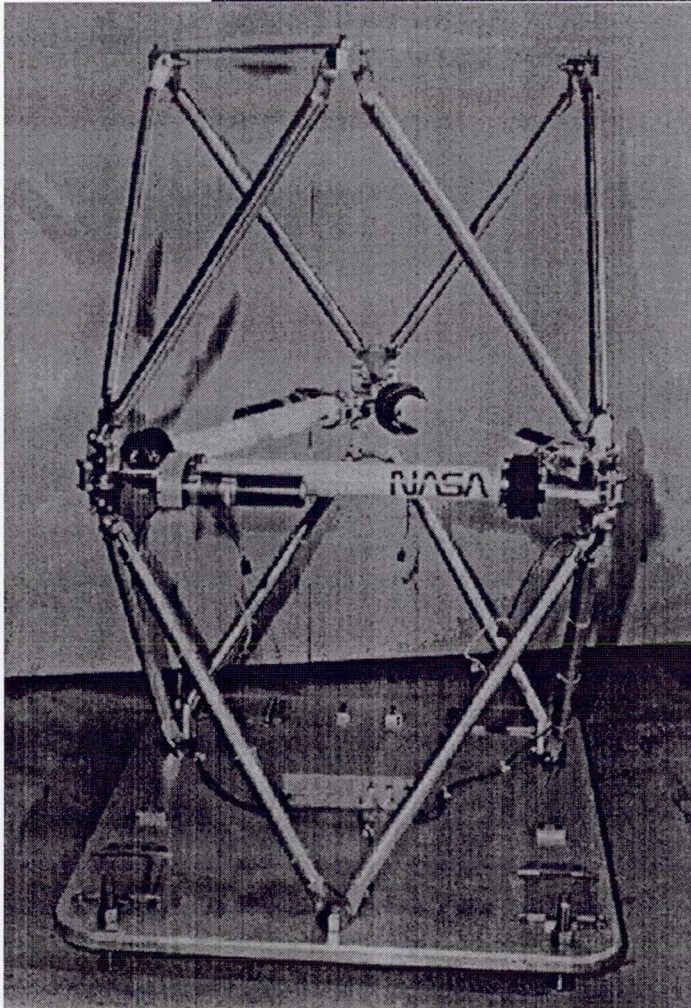
- **Langley Smart Materials Infrastructure**
- **Materials Research**
- **Applications**
- **Summary**

Structural Types



Active Structure

(Example)

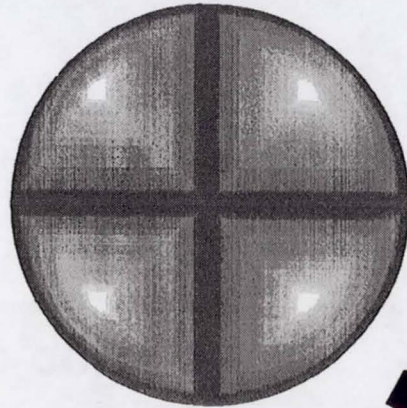


**Variable
Geometry
Truss**

Smart Structure

(Example)

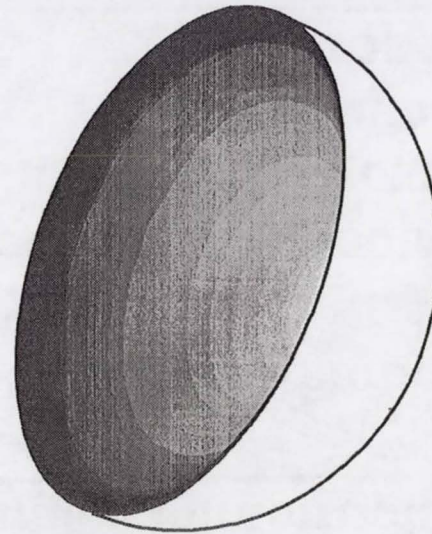
Piezoelectric
Polymer
Film



Electric
Field



- Tunable Parabolic Reflectors
- Adjustable Fresnel Lense



Shape change for focusing

Langley Smart Structures Overview

Langley Infrastructure

Materials

Research

- Advanced materials
- New process methods
- Improved properties
- Piezo-composites

Fabrication

- Mat'l processing
- Electroding
- Poling
- Bonding

Characterization

- Electrical req'ts
- Stress vs. strain
- Static & dynamic properties

Technology

Acoustics
& Noise

Aeroelasticity

Vibration
Control

Applications

Cryopump

Active
Landing Gear

Active
Mount

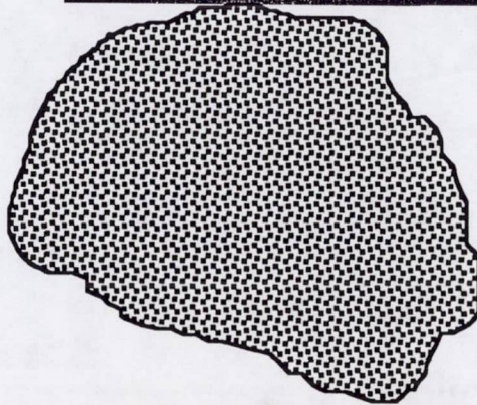
Materials Research

- **Ceramics**
- **Polymers**
- **Polymer-Ceramic composites**

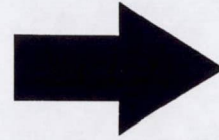
Ongoing Smart Materials Research

	Objective	Team
Ceramics	• Evaluate sensor/actuator response • Optimize process	Langley, Clemson, AURA Ceramics, PCB Piezotronics
Polymers	• Develop new piezoelectric polymers with enhanced --thermal --chemical --electrical properties	Langley, Triton Systems
Polymers - Ceramic Composites	• Develop novel materials by combining: --piezoceramics --polymers	Langley, Triton Systems

μ -Composite



39 Polyimide coated powders



Molding process
(Heat & pressure)

Multitude of solid
objects having high
powder content (97%)



Polyimide/Ceramic Blends
(Piezoelectric blends)

RAINBOW Ceramics

(Reduced And Internally Biased Oxide Wafers)

- High temperature reduction of standard piezoelectric ceramic wafer
 - Monolithic structure
 - Piezoelectric layer
 - Metallic layer
 - Metallic layer contracts causing wafer to dome

Piezoelectric
layer

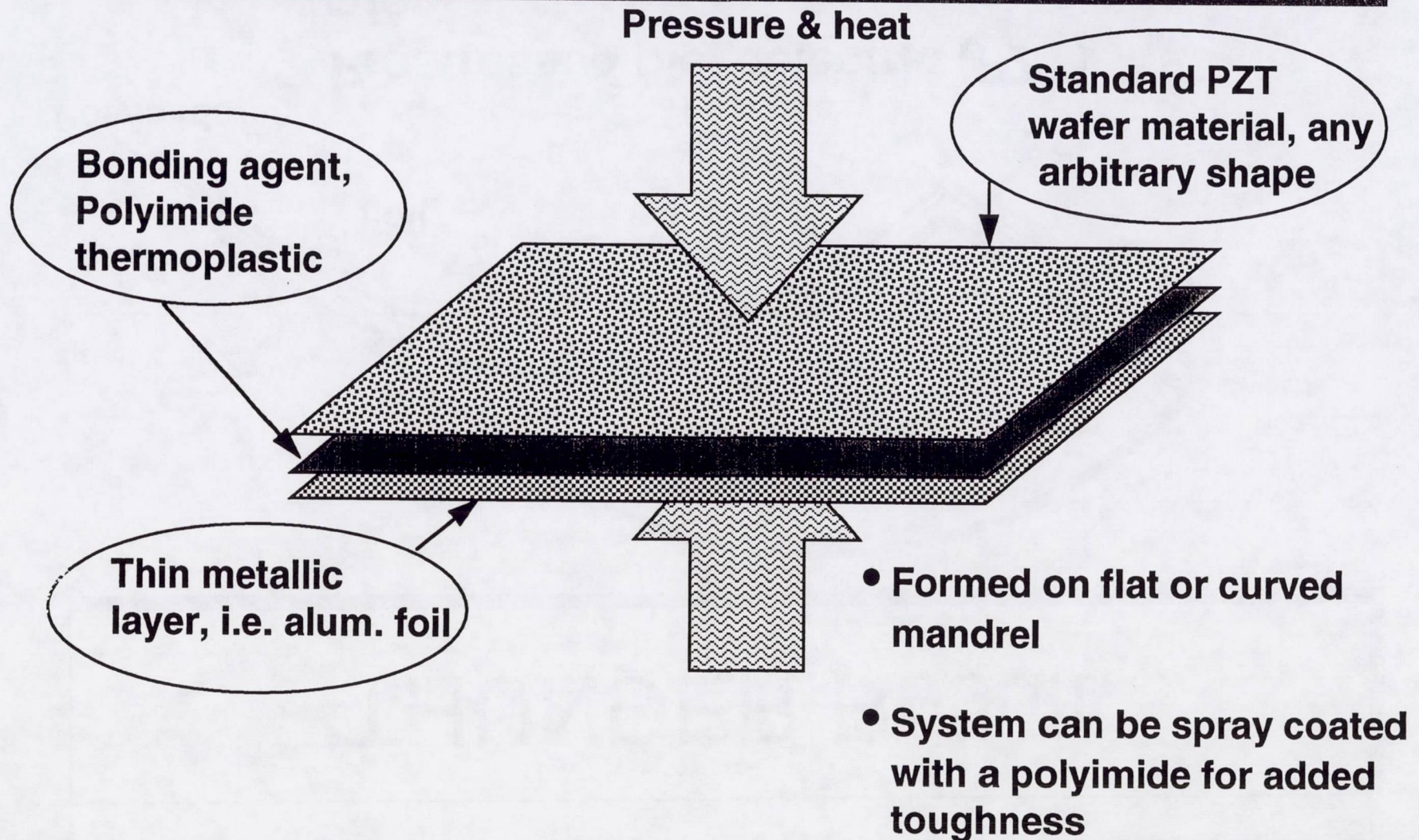


Metallic layer

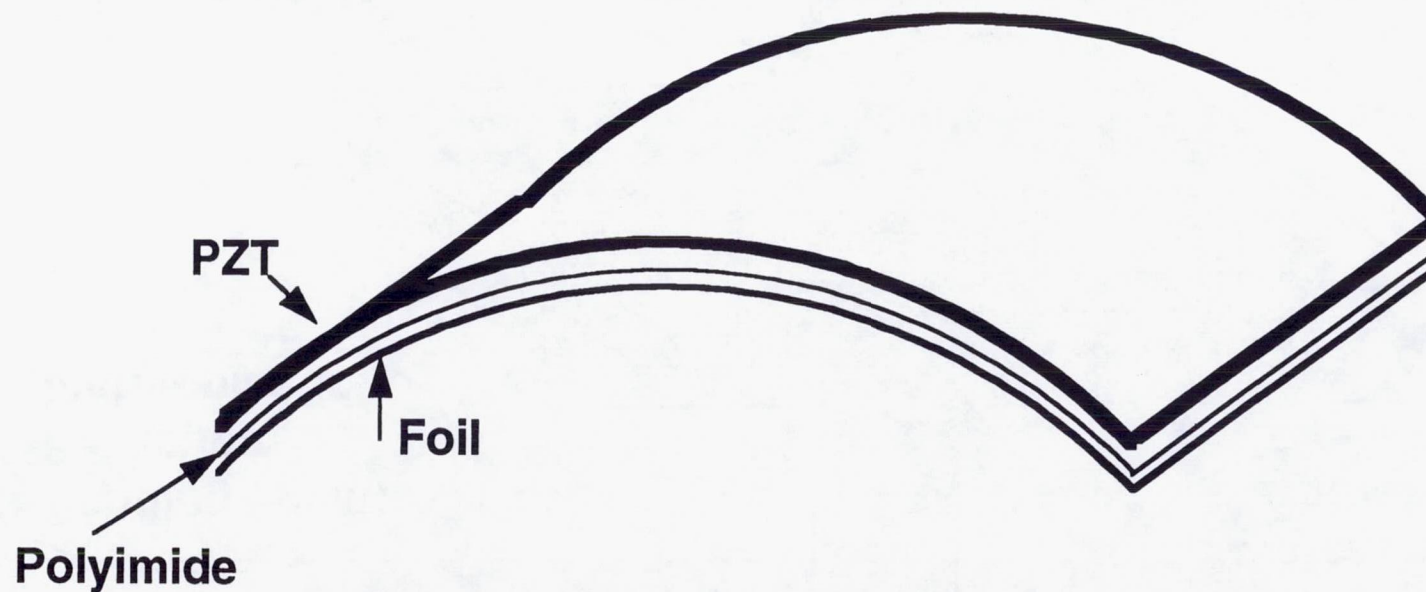
Rainbow x-section

THUNDER Process

(Thin-layer composite UNimorph piezoelectric Driver and sEnsoR)



THUNDER Result

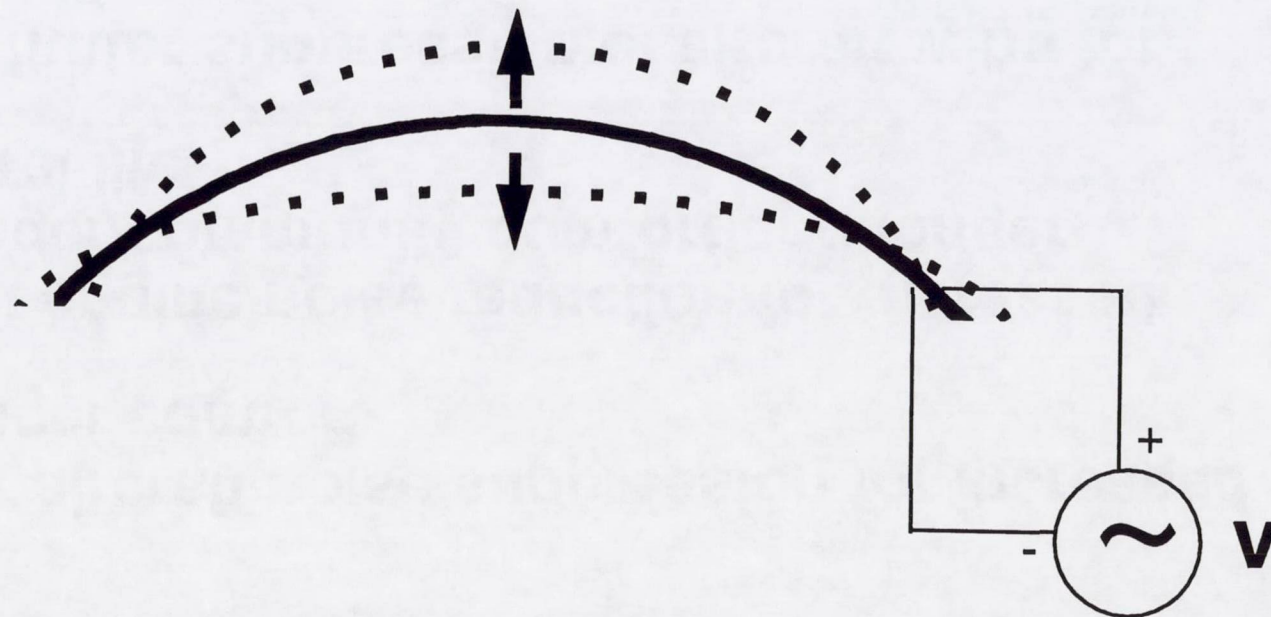


- Prestressed piezoelectric (PZT) wafer

Upon cooling, curvature is induced due to difference in thermal expansion between the PZT wafer & foil.

RAINBOW & THUNDER

Motion



Applications

- **Interior aircraft noise suppression for increased passenger comfort**
- **Aircraft engine noise reduction for increased passenger/community comfort and longer structural life**
- **Active flutter suppression of aircraft wing for better performance**
- **Active shape control of polymeric reflectors with smaller distortions and reduced weight**
- **Aircraft wing distortion to eliminate control surfaces**

New Devices

- **“Rainbow” piezoelectric pump for cryocooler applications**
- **Large linear motion or “inchworm” motors requiring no lubrication**
- **Active instrument mount**
- 45 • **Low-cost piezoelectric stack wafers from a new blend of piezoelectric ceramics and polymers**
- **“Rainbow” piezoelectric ceramic wafers for micro-motion applications in optical systems**
- **Active trim panel for noise reduction**

Summary

- **Infrastructure being developed**
- **Potential piezoelectric polymers**
- **Applying piezoceramics to suppress**
 - aircraft noise
 - aircraft wing flutter
 - spacecraft vibrations
- **Pursuing active landing gear concepts**

Smart Materials Research at NRL

Peter Matic

Mechanics of Materials Branch

Naval Research Laboratory

**4th Annual Advances in Smart Materials for Aerospace
Applications Workshop**

NASA Langley / May 4-5, 1995

32-27
6/4/16
025088
401.

Outline

Introduction

Sensors

Actuators

Modeling and Control

Summary

Introduction

Materials technology developments

- Decreasing sizes of basic components
- High quality in large quantities
- Integrated and highly coupled systems concepts

Choices in analysis strategies

- Local versus systems approach
- Discrete versus continuum viewpoint
- Selection of computational architectures

Investigators

Sensors

- Charlie Askins
- Joe Friebele
- Alan Kersey

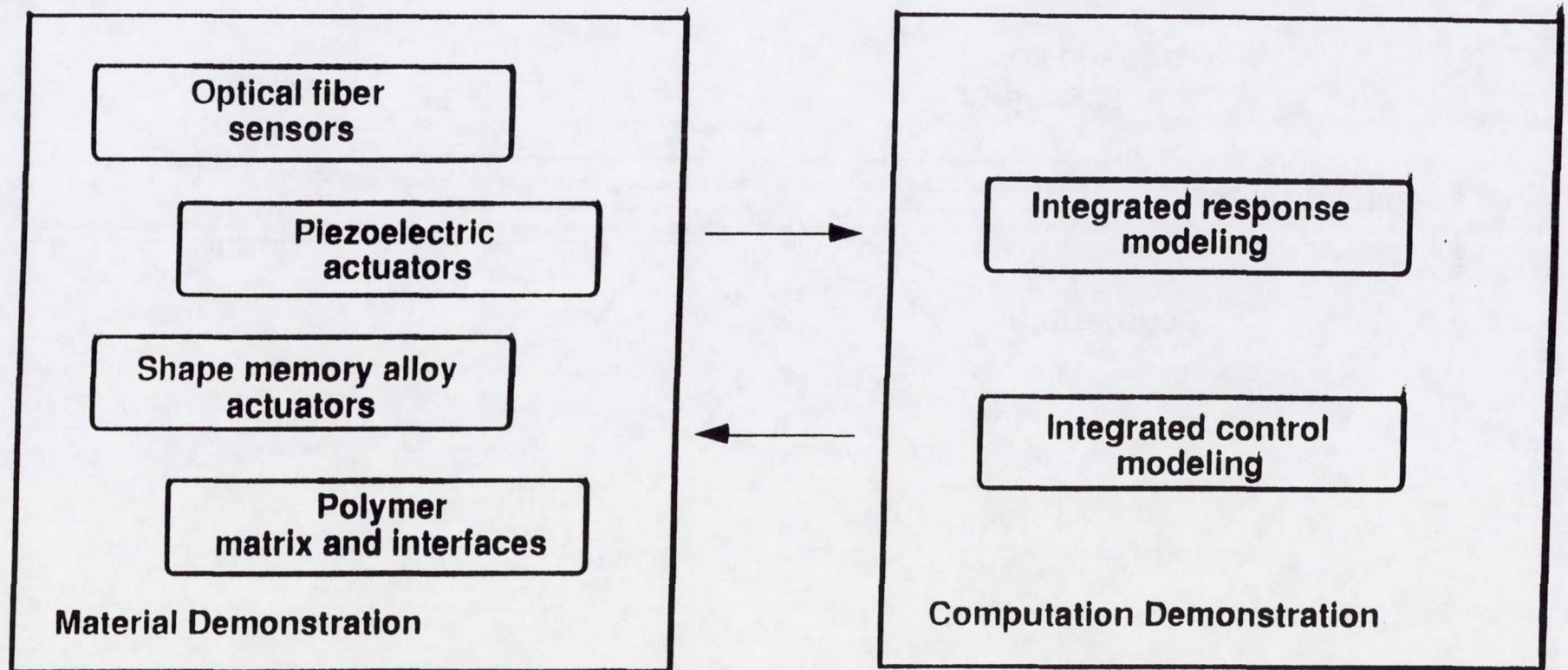
Actuators

- Mark Chase (Potomac)
- Manfred Kahn
- Dan Krause
- Steve Sullivan

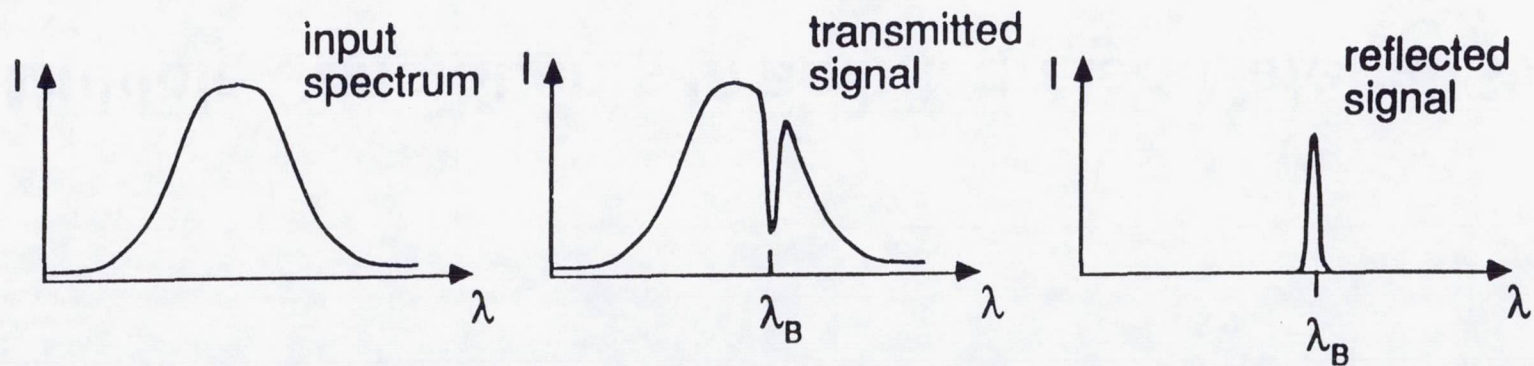
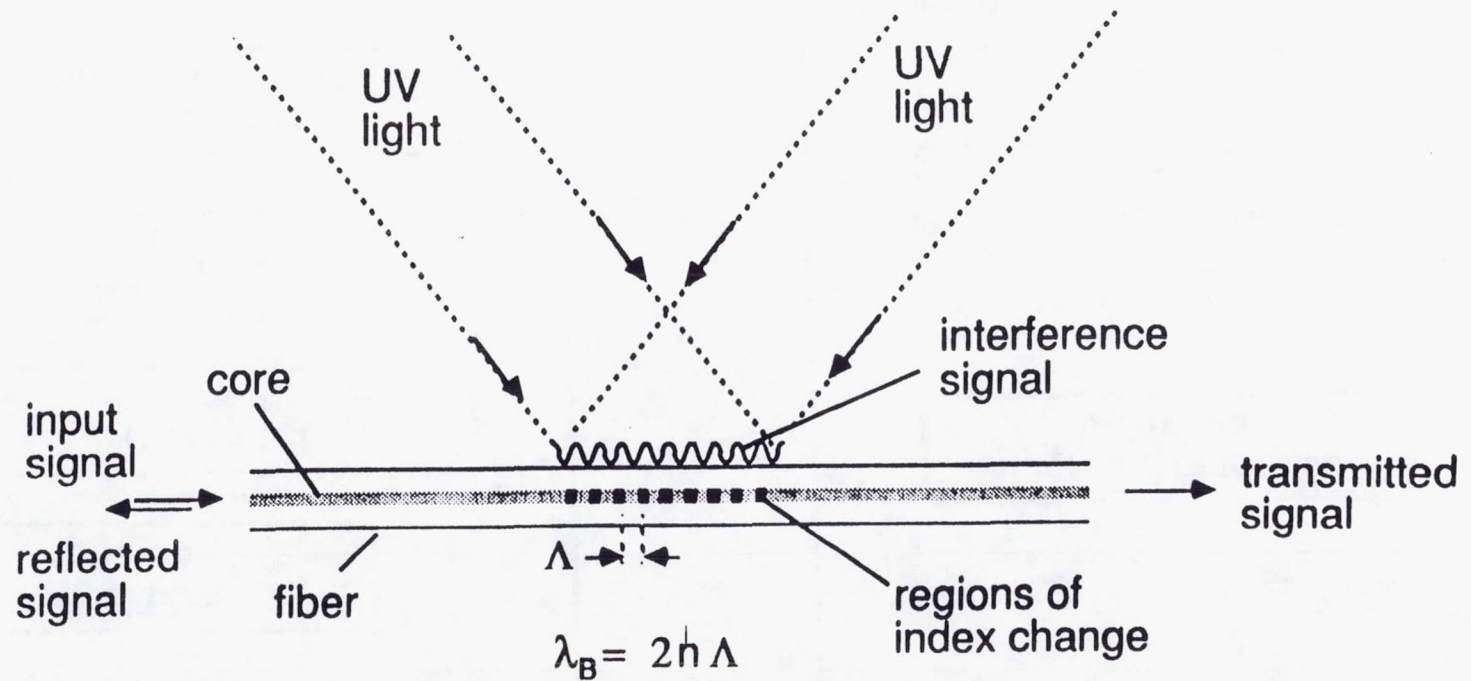
Modeling and Control

- Virginia DeGiorgi
- George Kirby
- Doug Lindner (VPI)
- Peter Matic

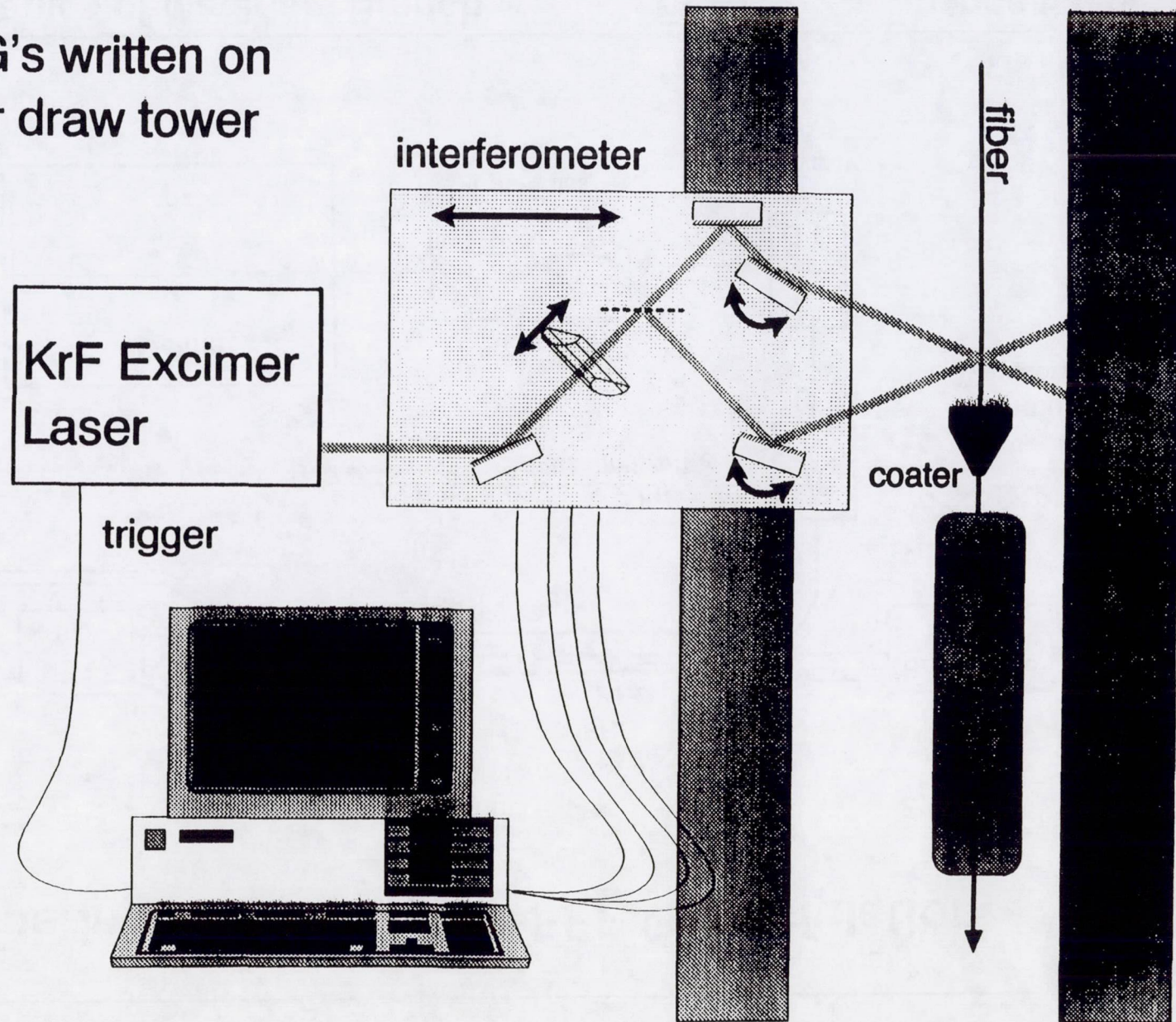
Multiple Constituents in an Integrated Material System



Fiber Bragg Gratings

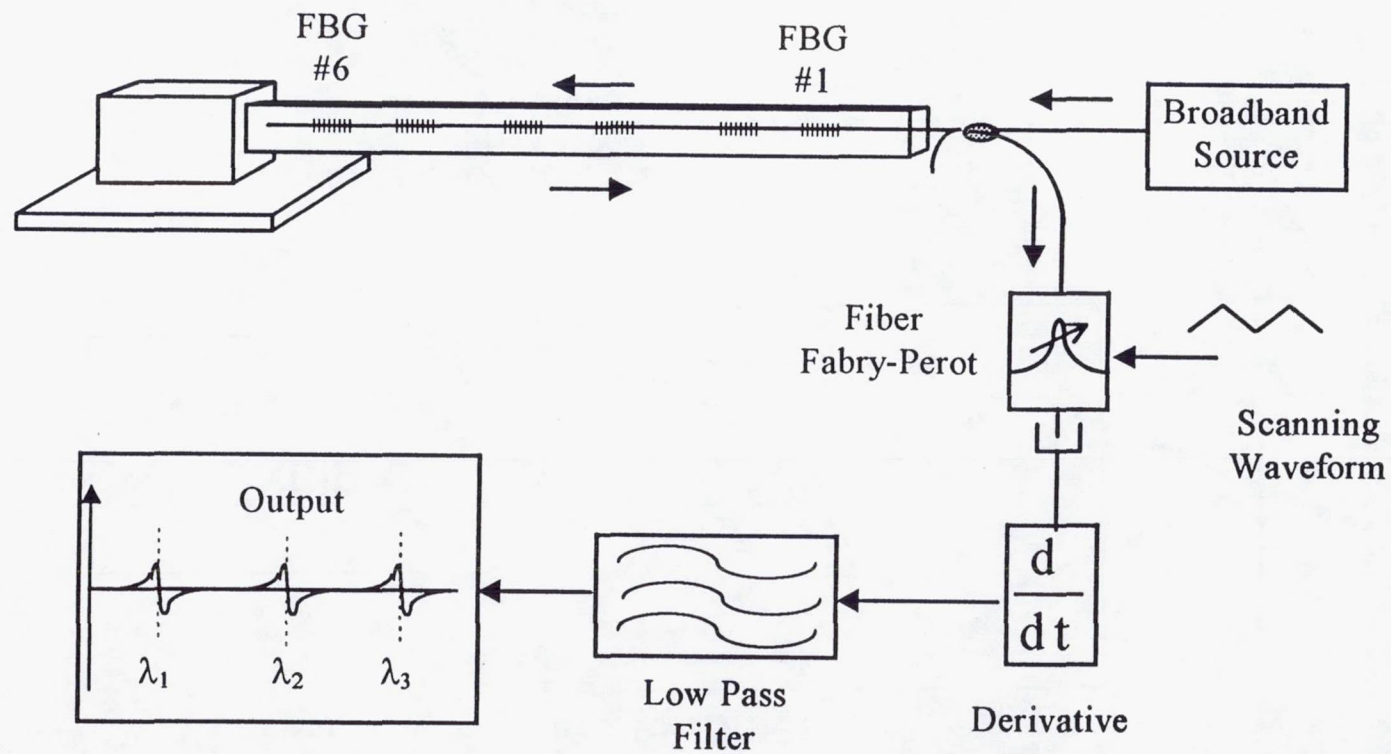


FBG's written on fiber draw tower





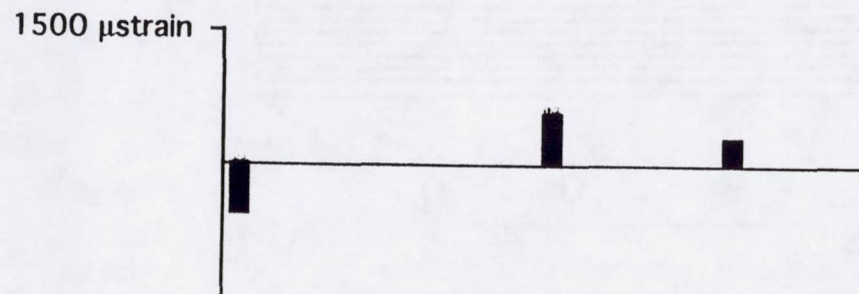
Experimental Setup and FFP Demodulation



Beam Shape Determination

NAVAL RESEARCH LABORATORY

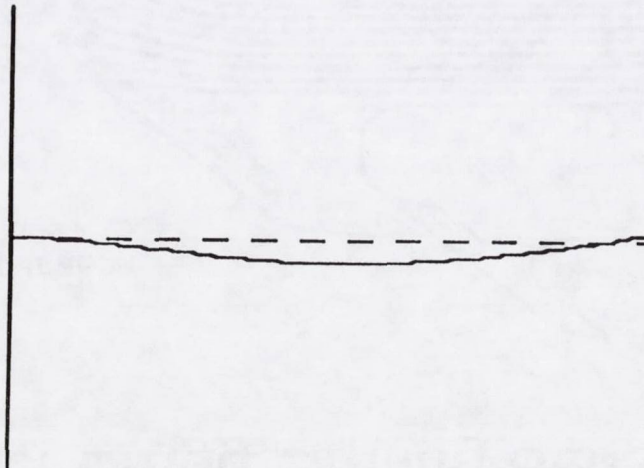
Grating Sensor Strain Levels :



Actual Beam Shape :



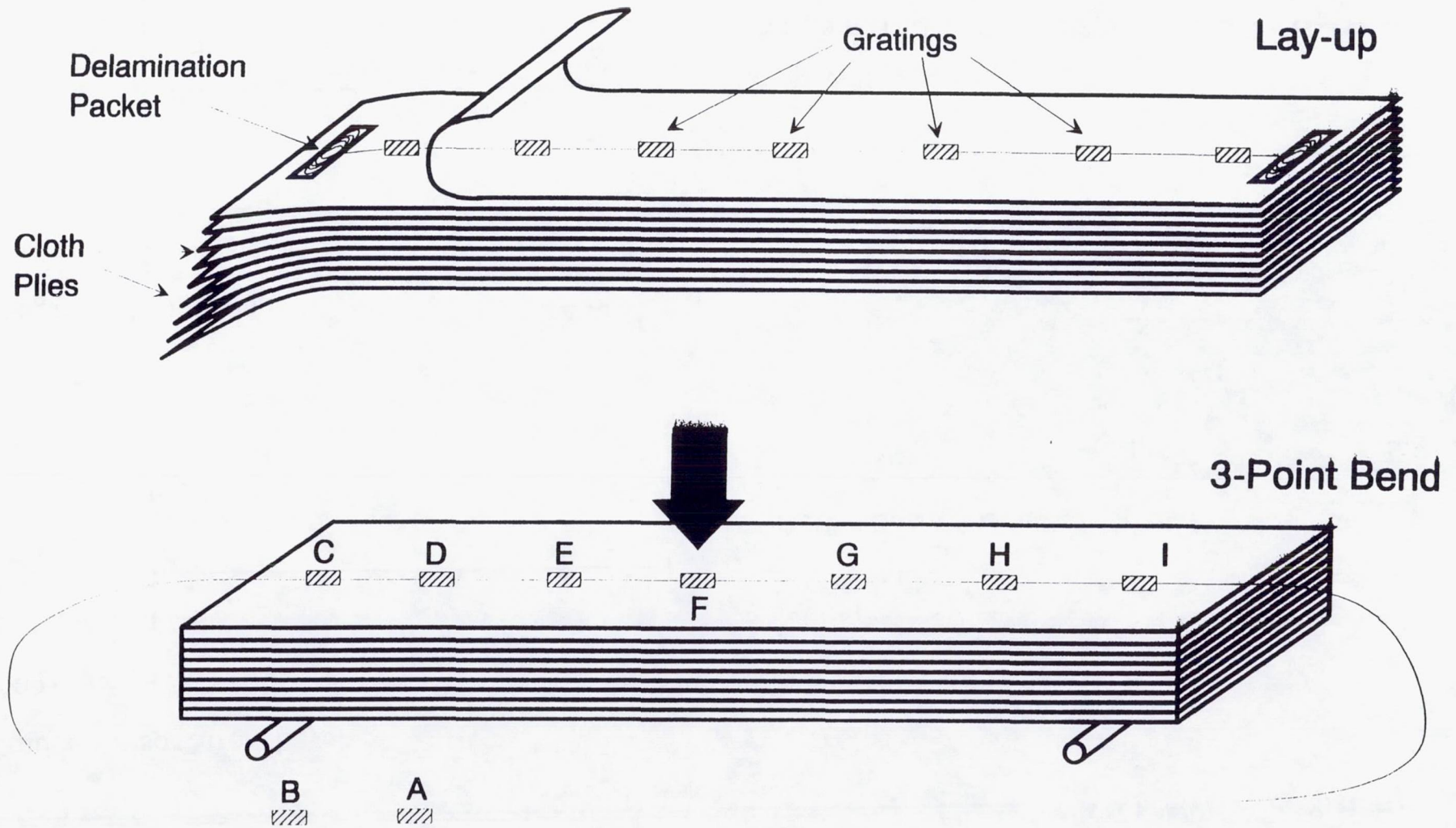
Calculated Beam Shape :

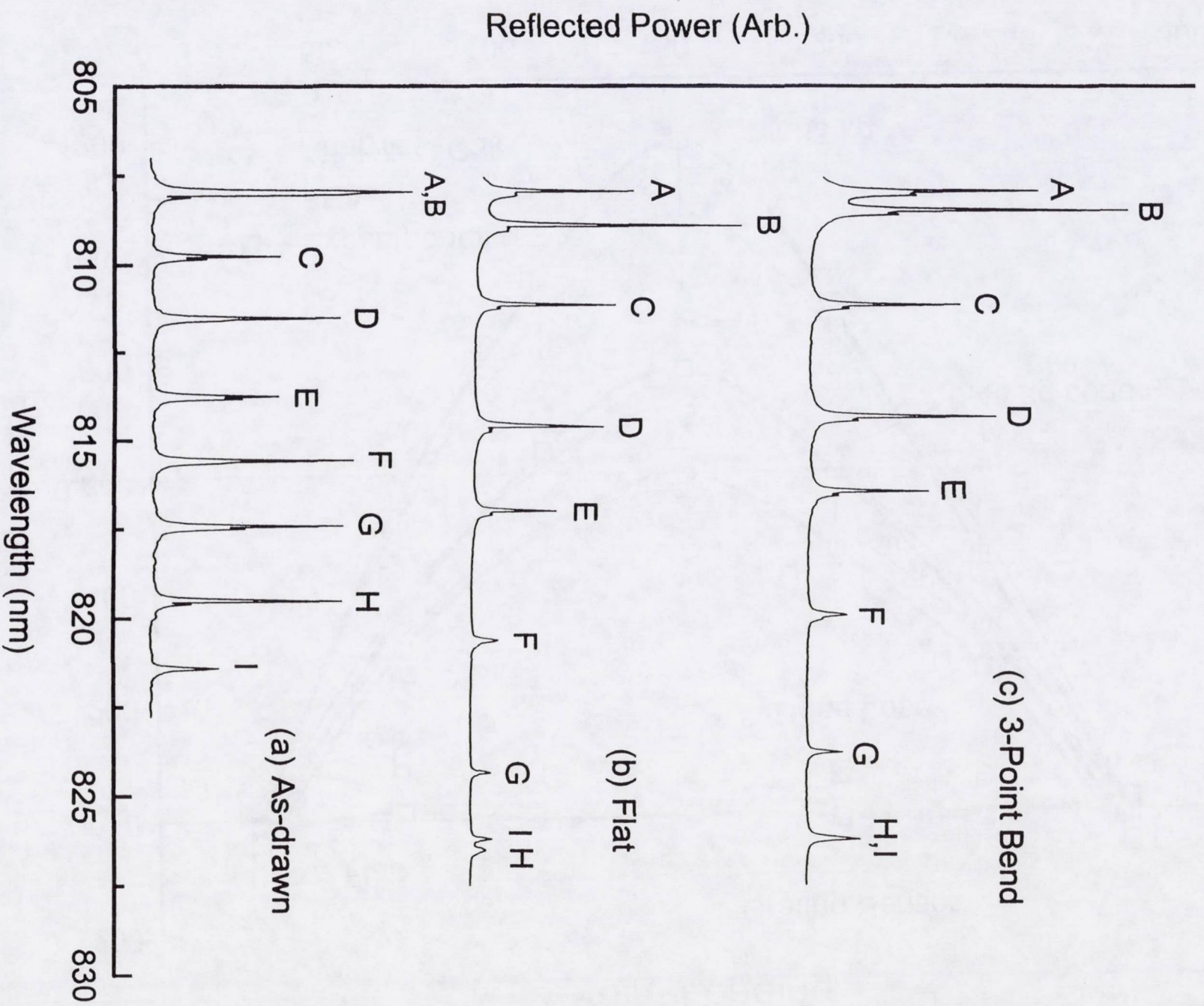


Component of :

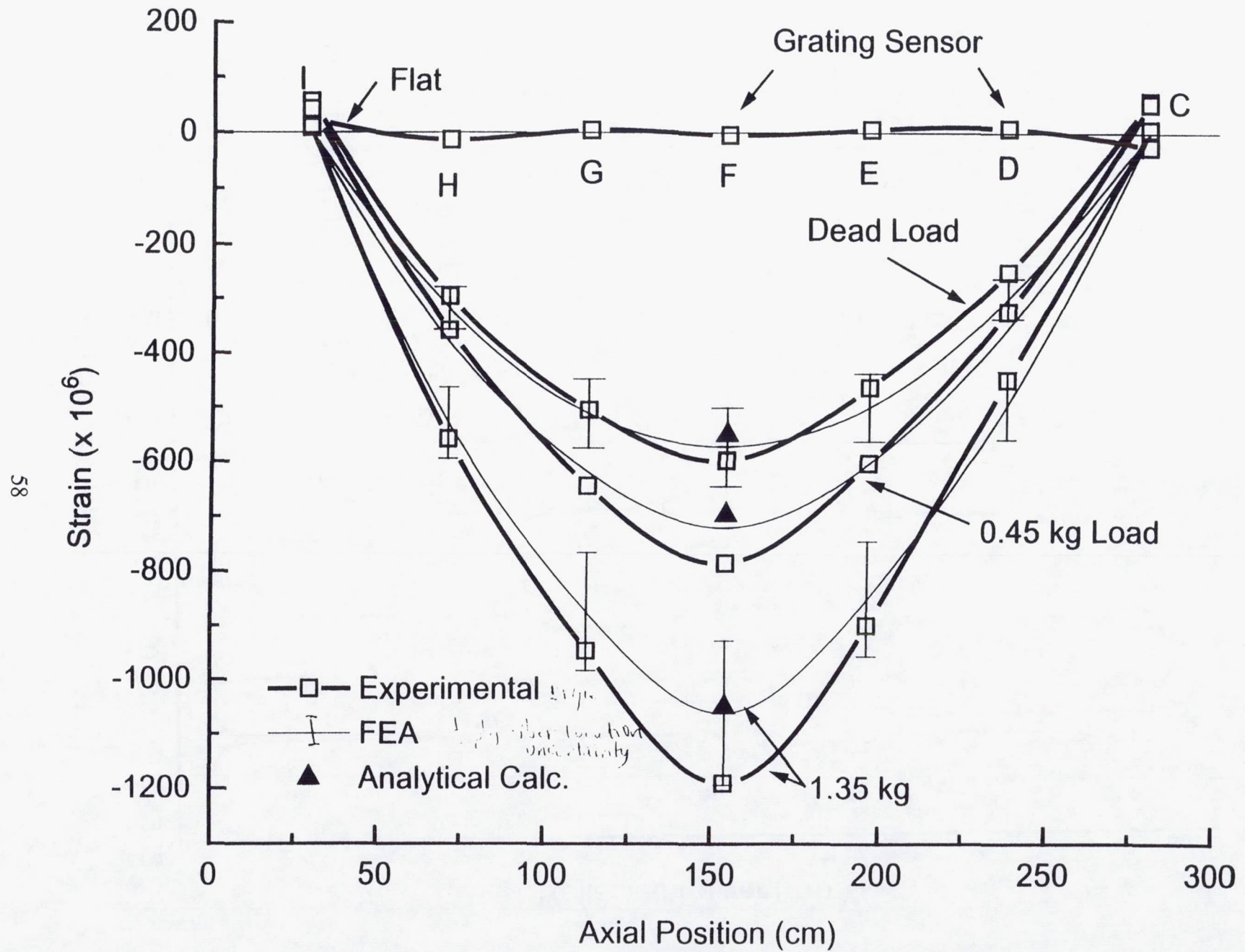
<u>Shape #1(a₁)</u>	<u>Shape #2(a₂)</u>	<u>Shape #3(a₃)</u>
-6.47	1.961	0.625

Fiber Bragg Grating Sensor Array in CRTM™ Composite

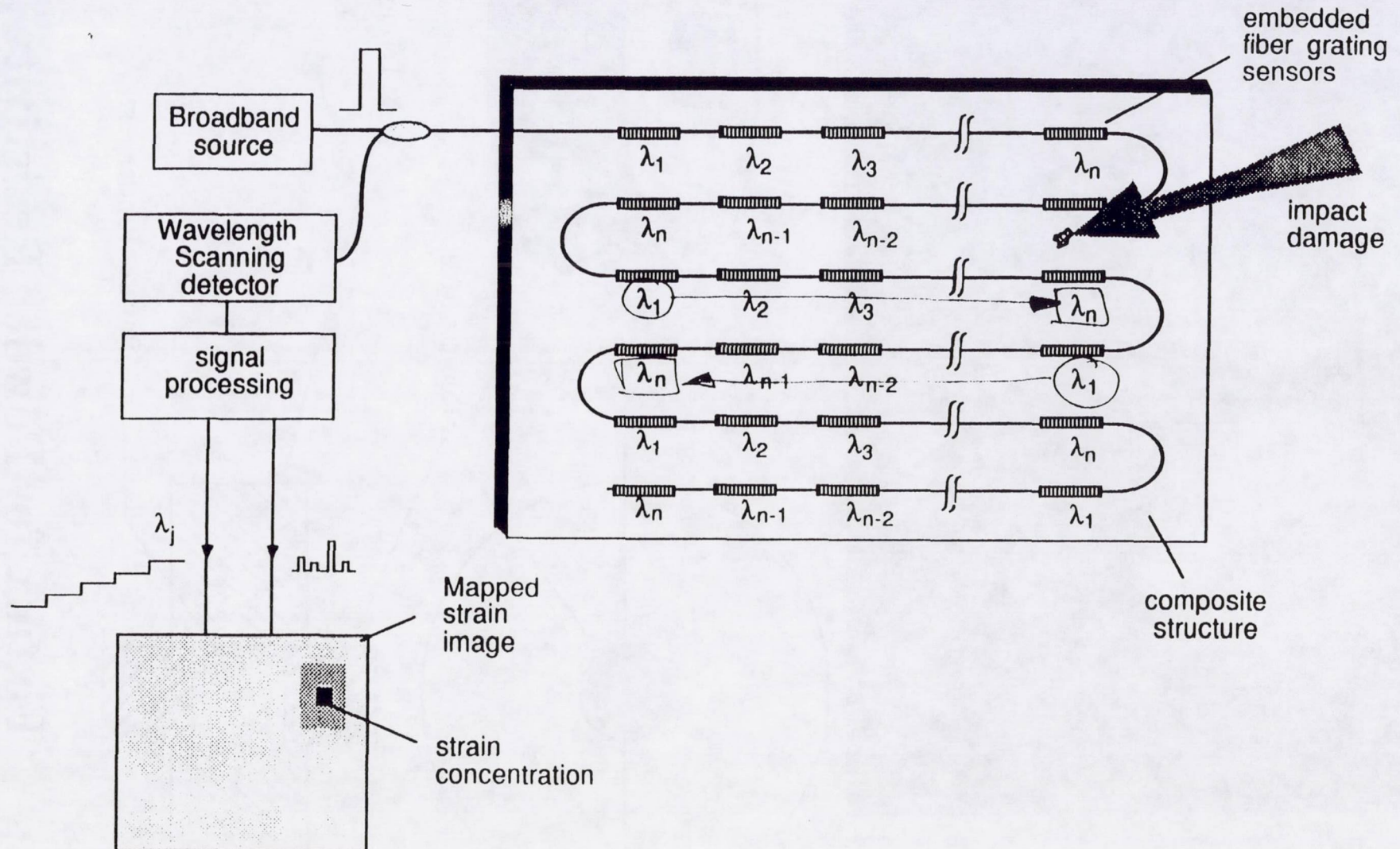


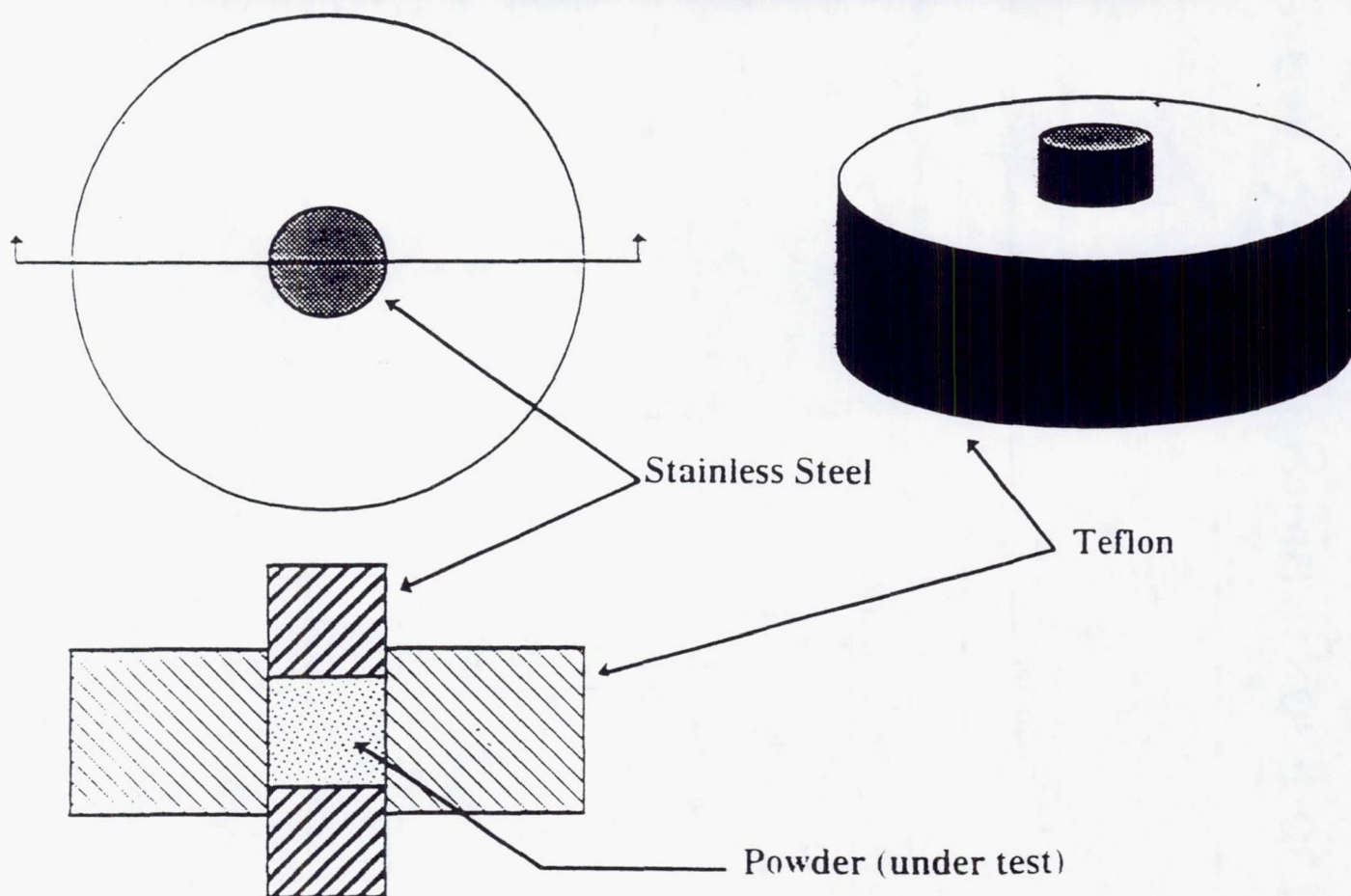
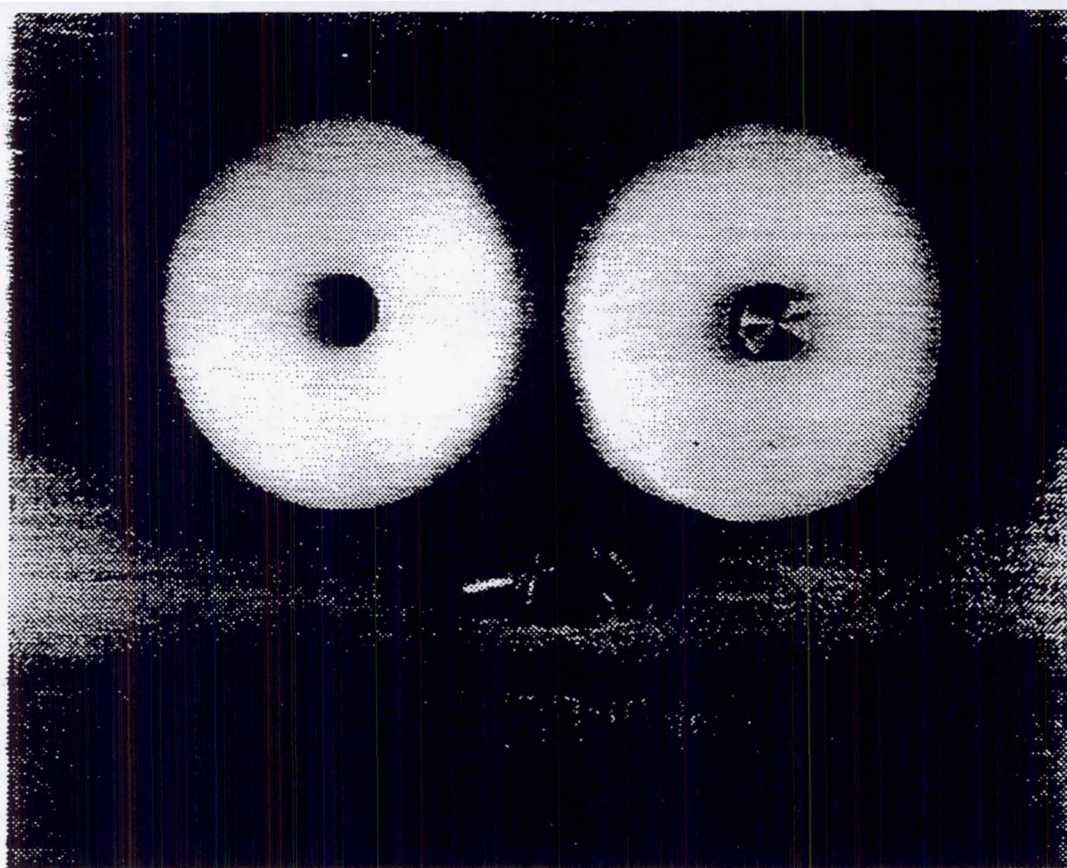


3-Point Loading

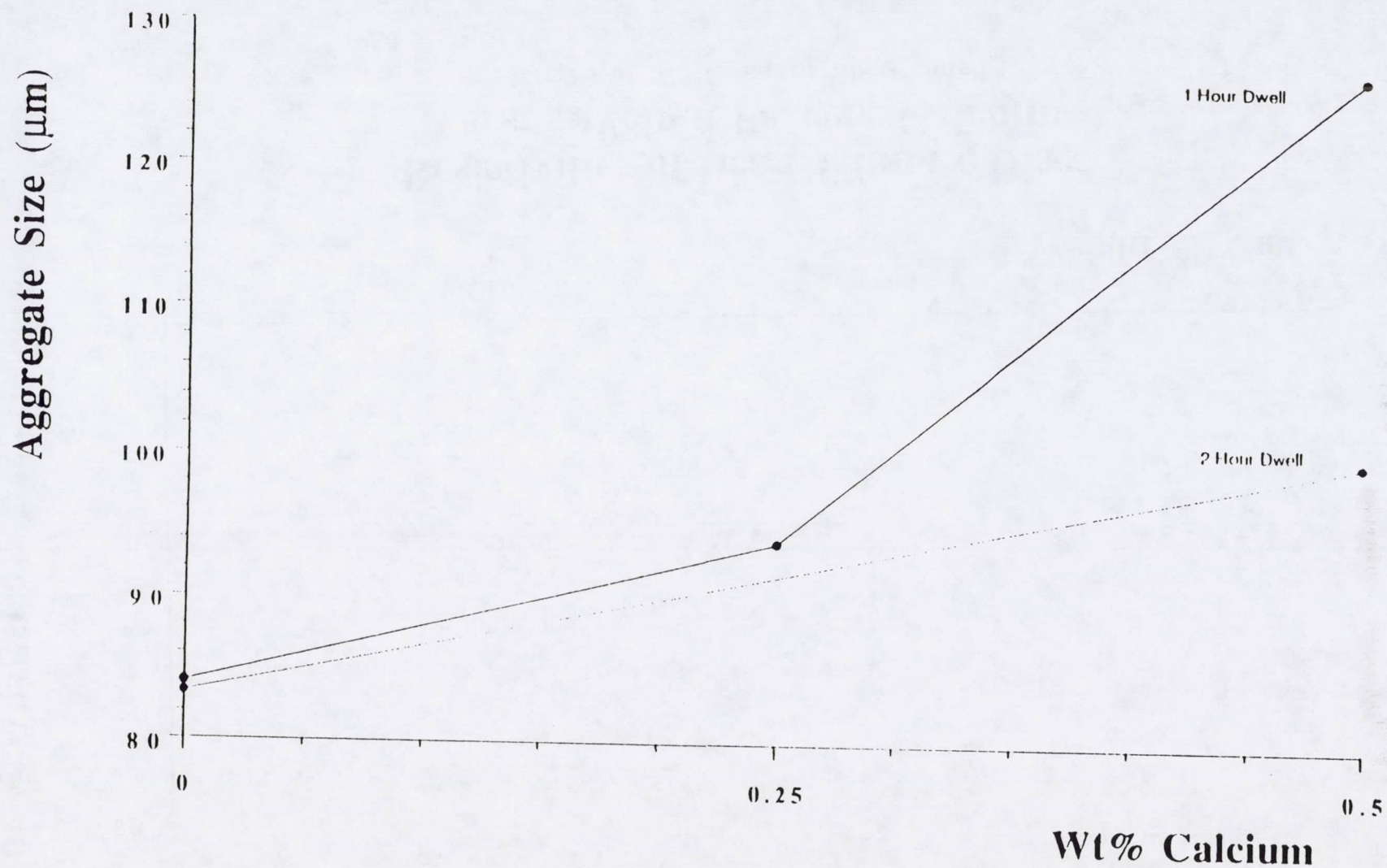


Distributed Strain Sensing by Wavelength Encoded Gratings



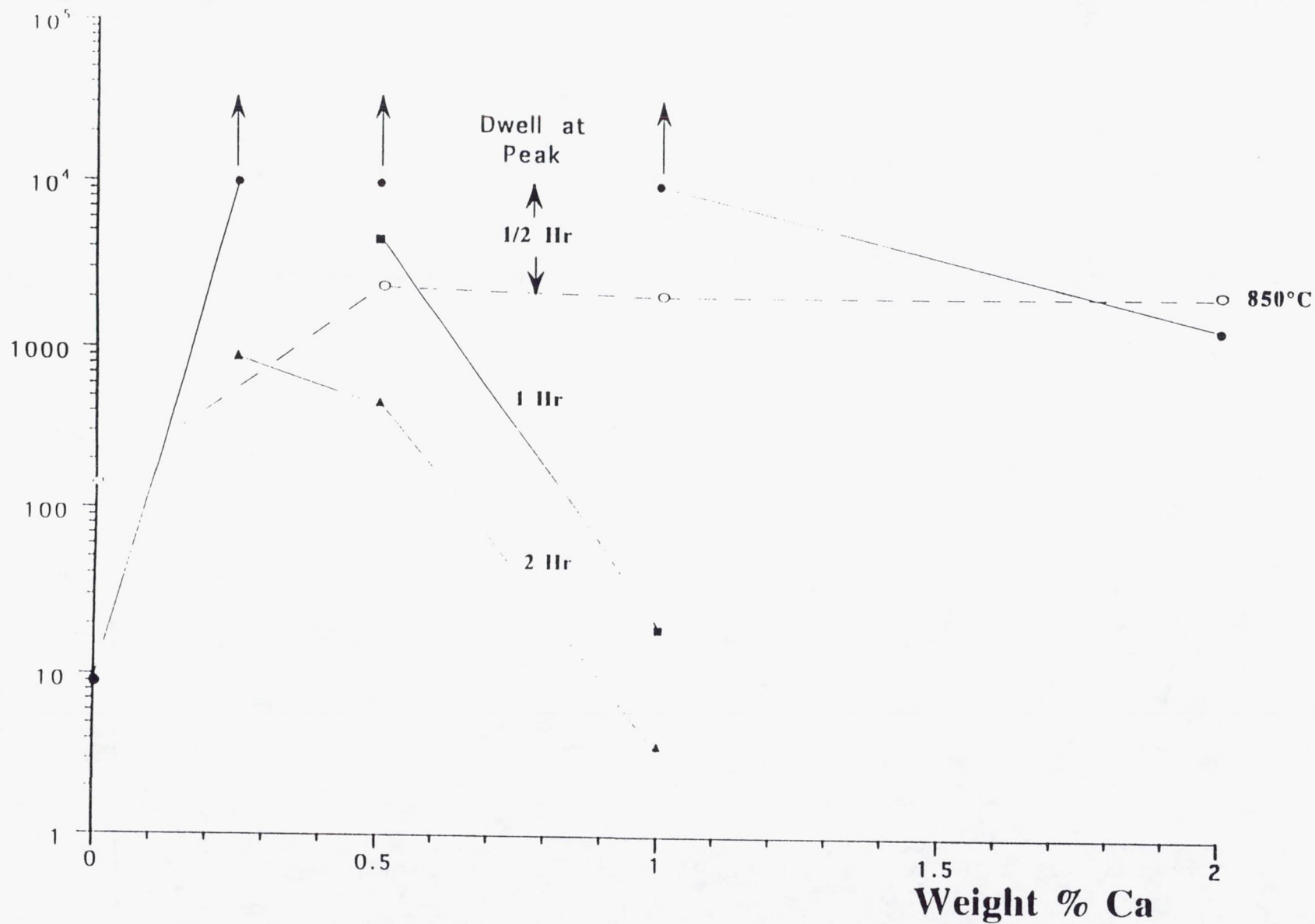


**Fixture for Powder Resistivity
and Dielectric Measurements**



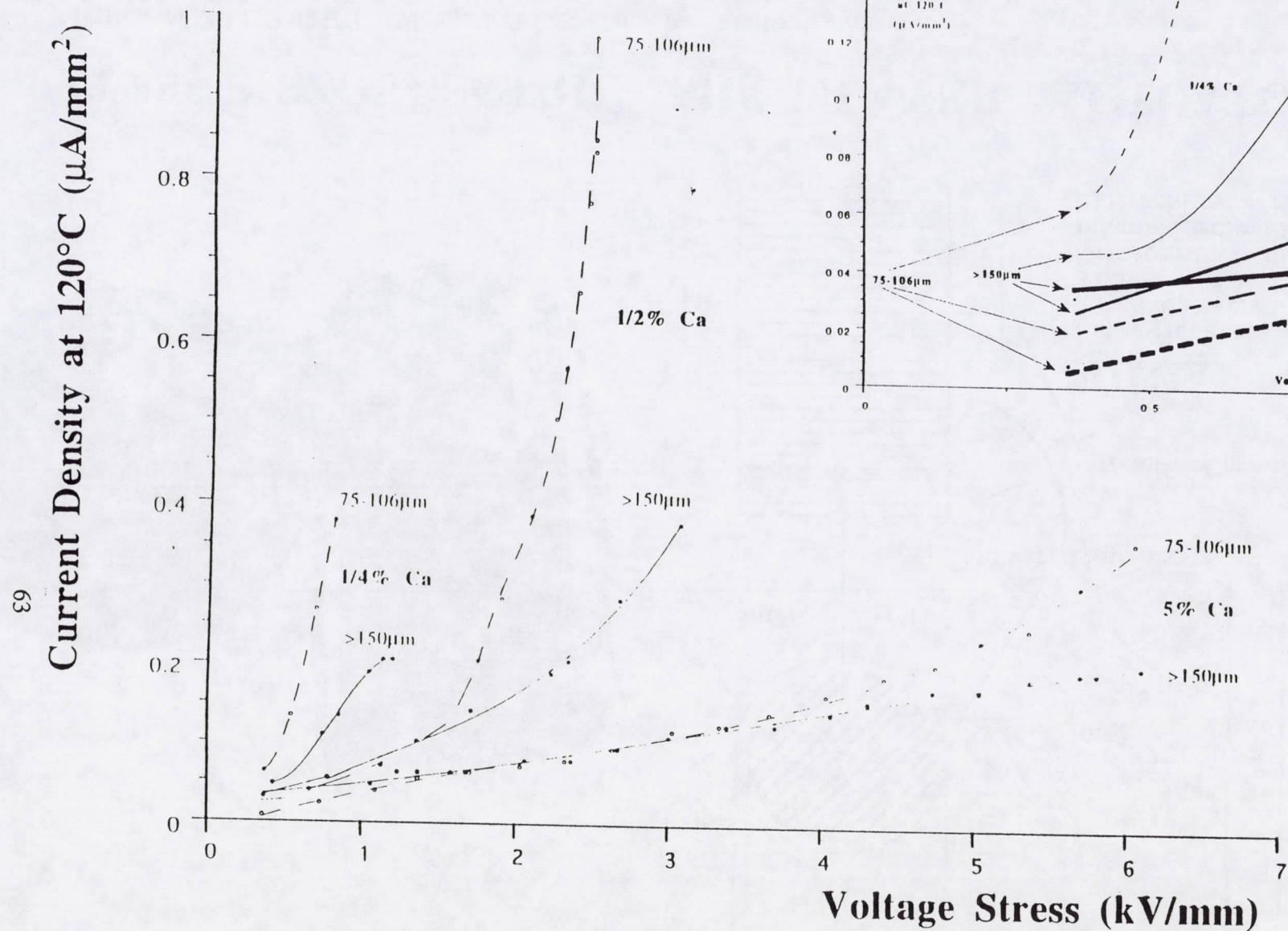
**Average Sizes of Aggregates From Broken Up Discs Sintered at 875°C
(After Screening)
Average Crystallite Size: 18 μm**

25°C Resistivity @ 40V/mm (GΩ-cm)

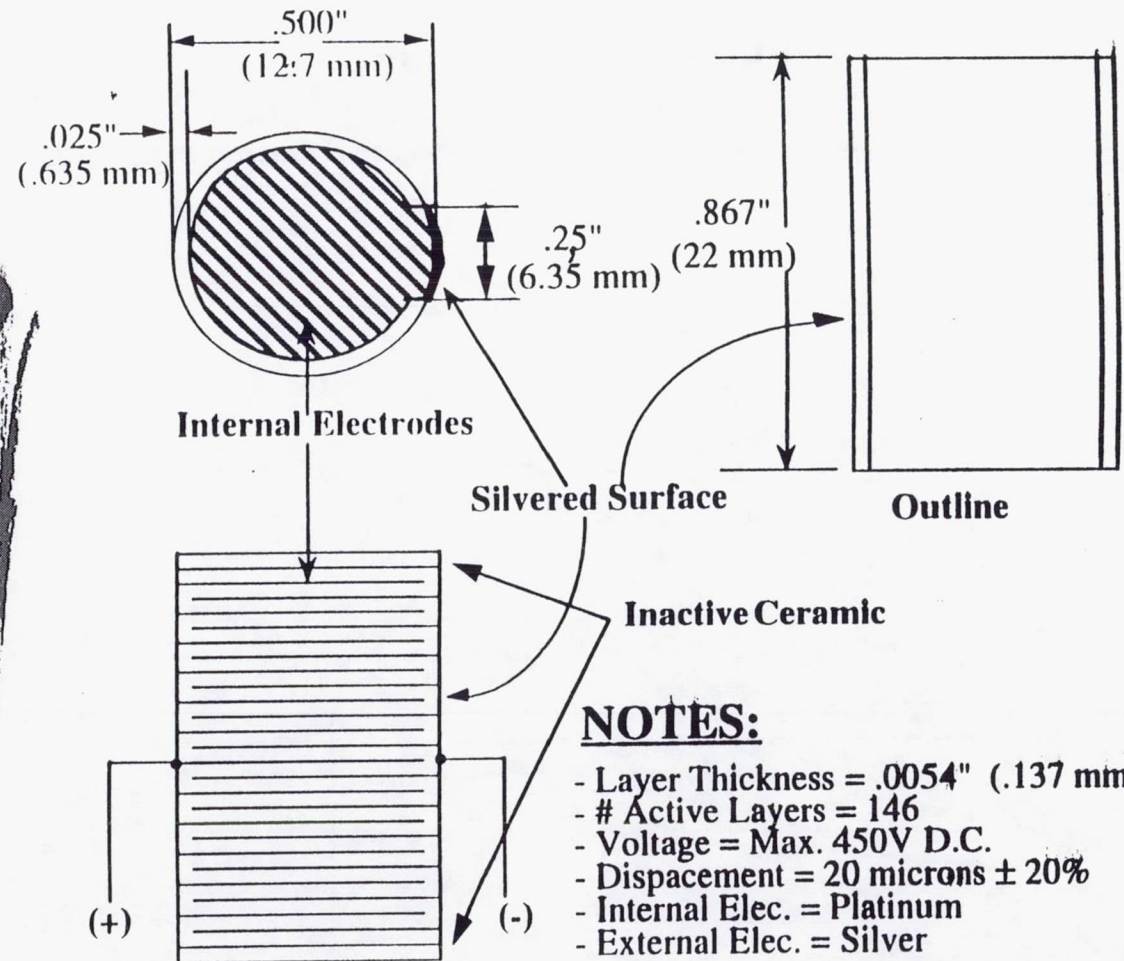
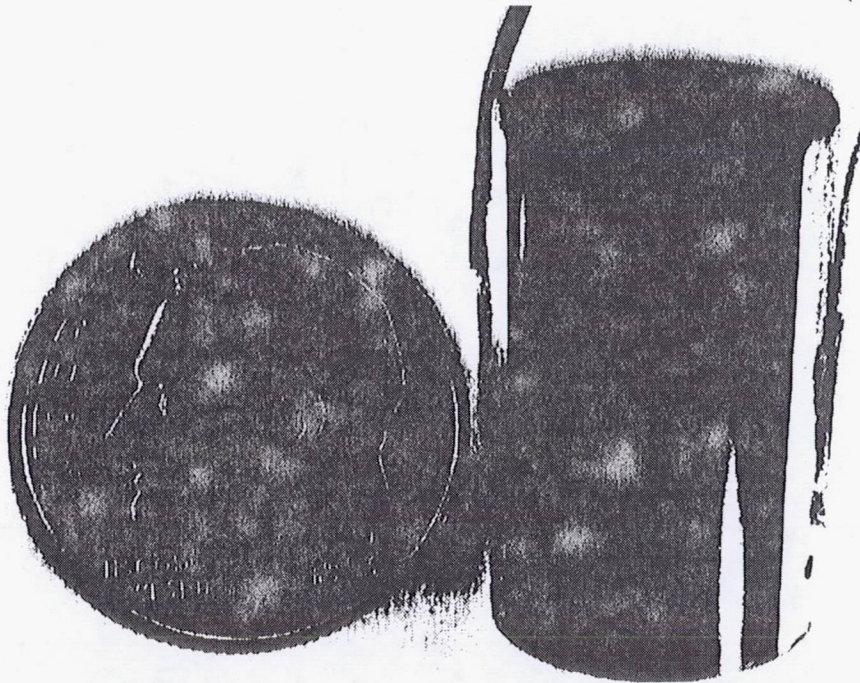


Resistivities of Lead Titanate Discs Versus Weight Percent Calcium

Sintered at 875°C except where noted

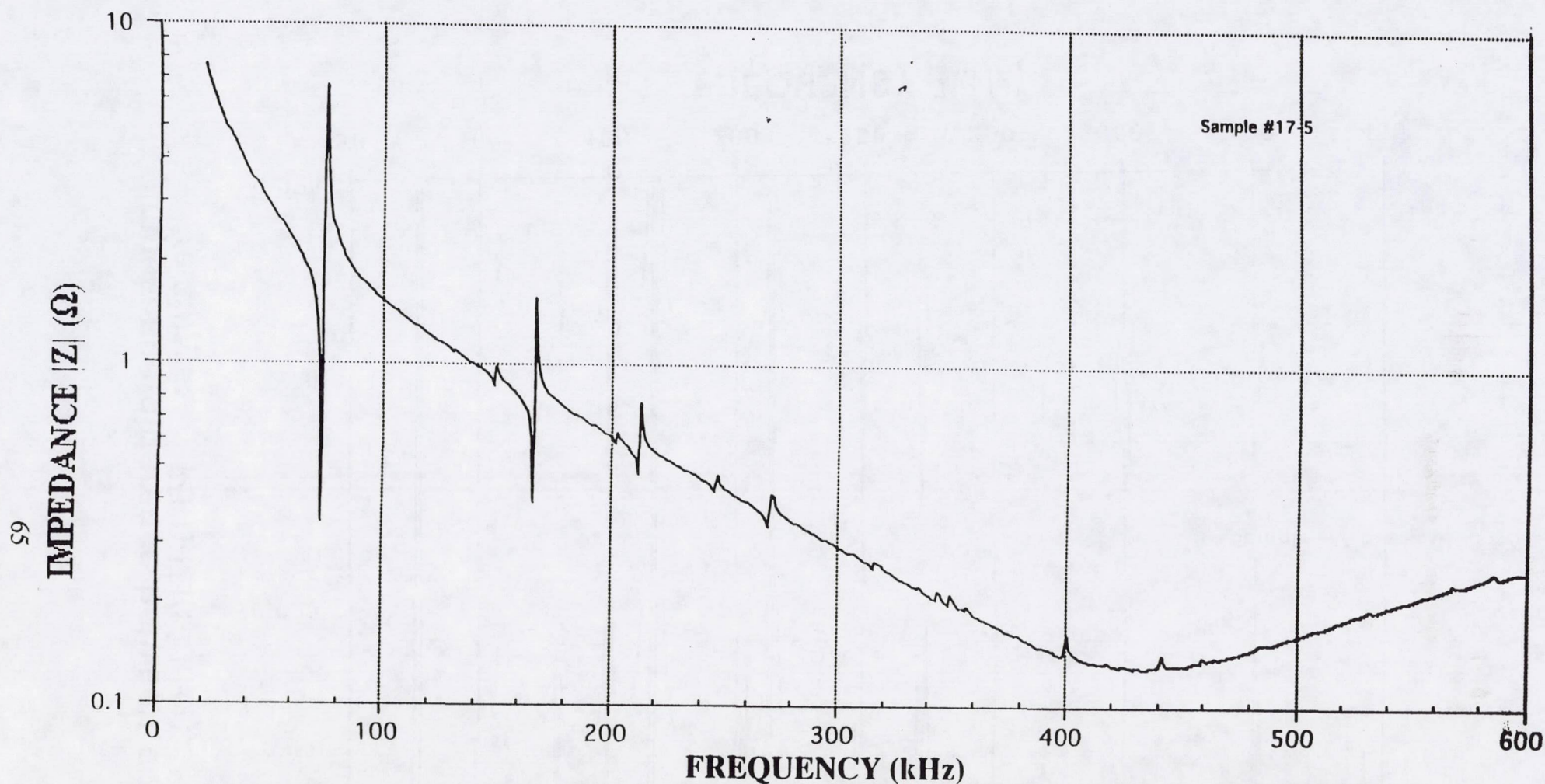


**Effects of Calcium and Aggregate Size on Current
 Through PT Particulates Treated at 875°C for 1 Hour**



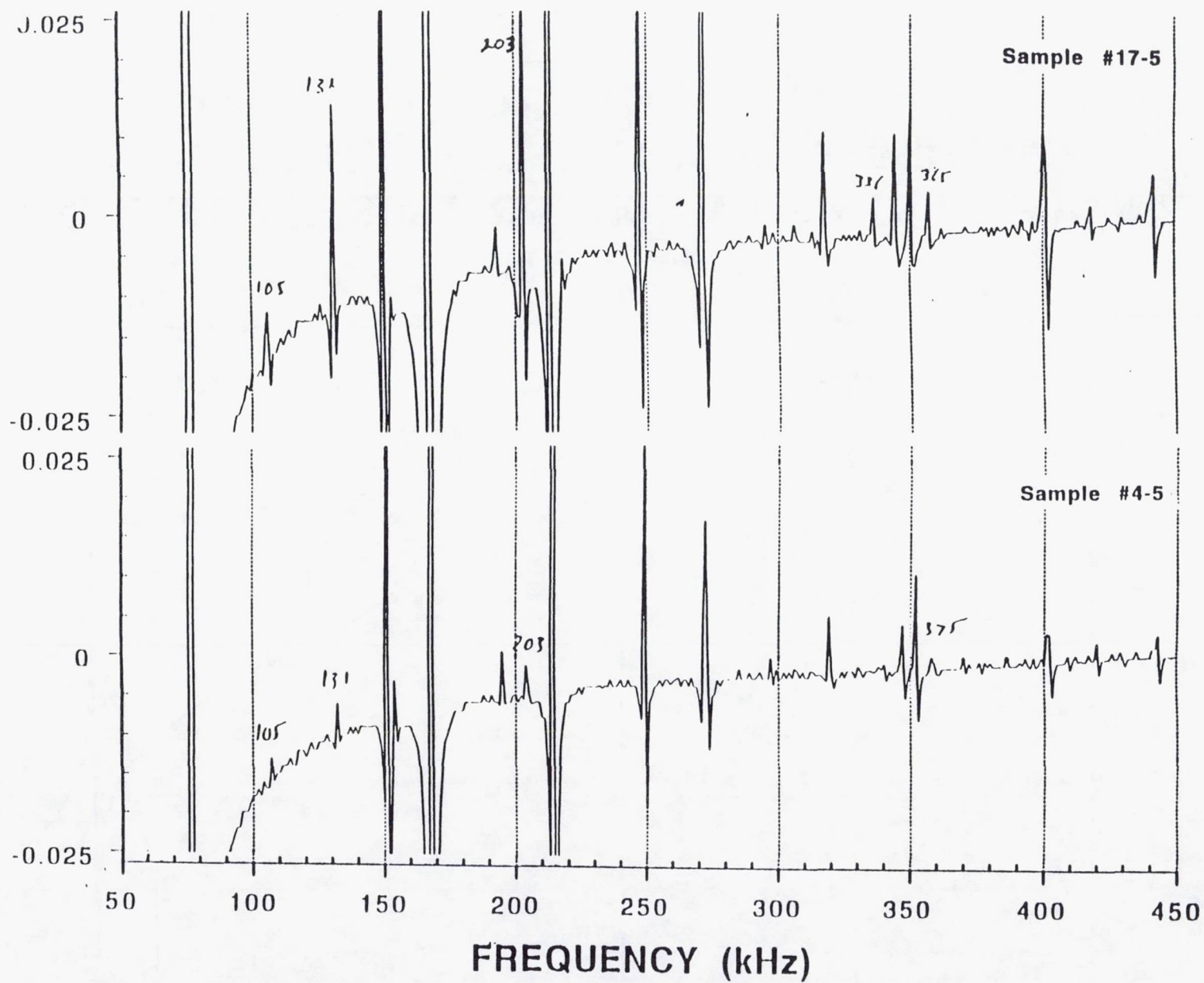
PZT 4S PIEZOELECTRIC MULTILAYER ACTUATOR *

*MORGAN MATROC INC, Electro Ceramics Division, Bedford, Ohio

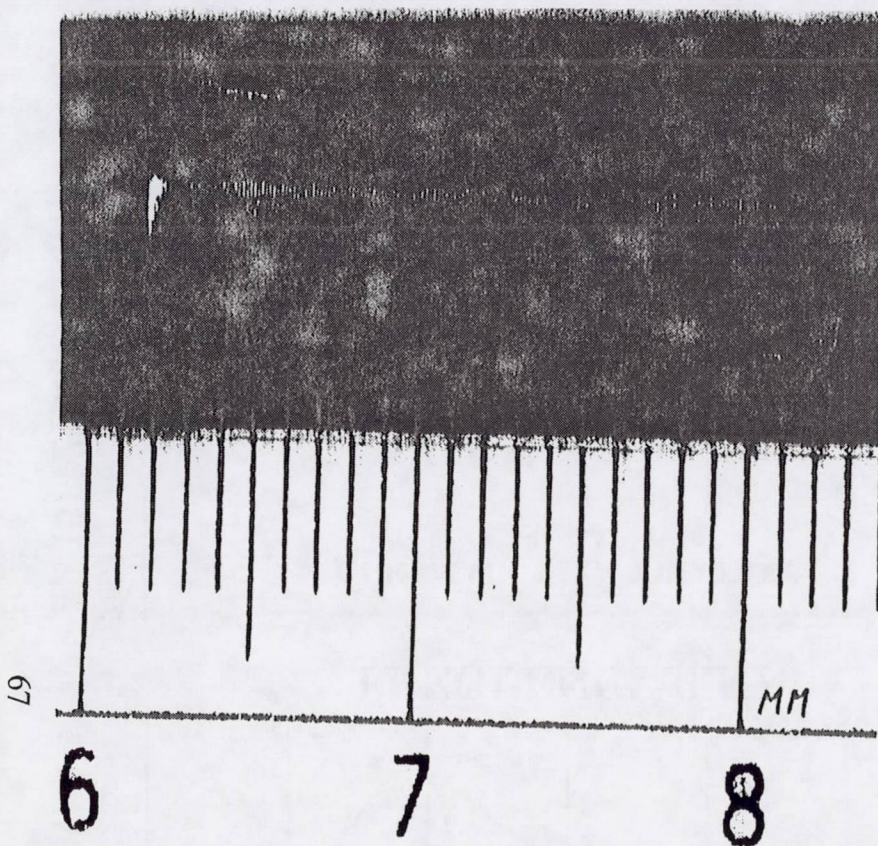


**IMPEDANCE VERSUS FREQUENCY OF A CRACK FREE
PIEZOELECTRIC ACTUATOR, $d_{33} = 10688$ pC/N
ON AN HP 4192A ANALYZER**

Impedance difference between consecutive
readings: $|Z(f) - |Z(f-1\text{kHz})|$, Ohms



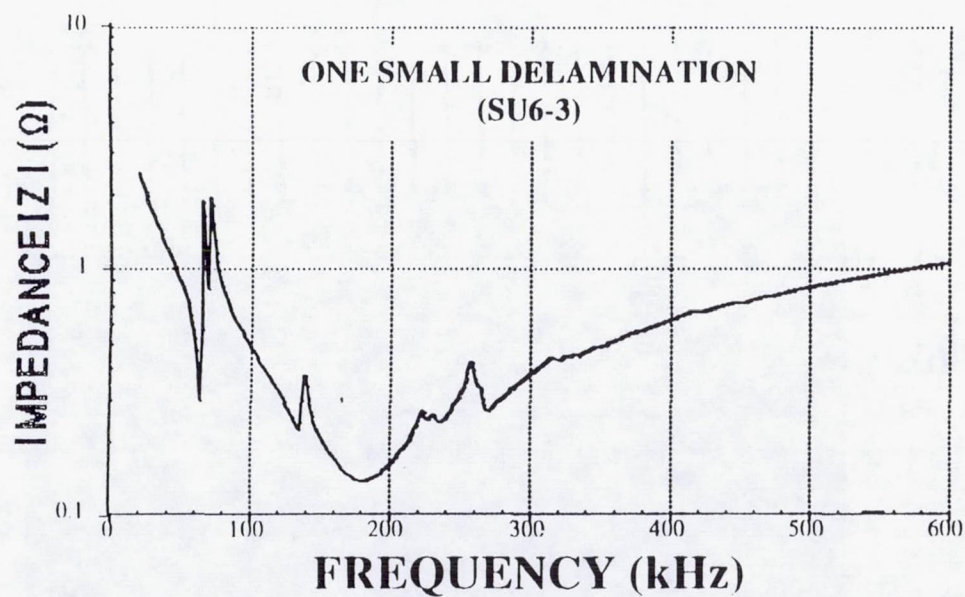
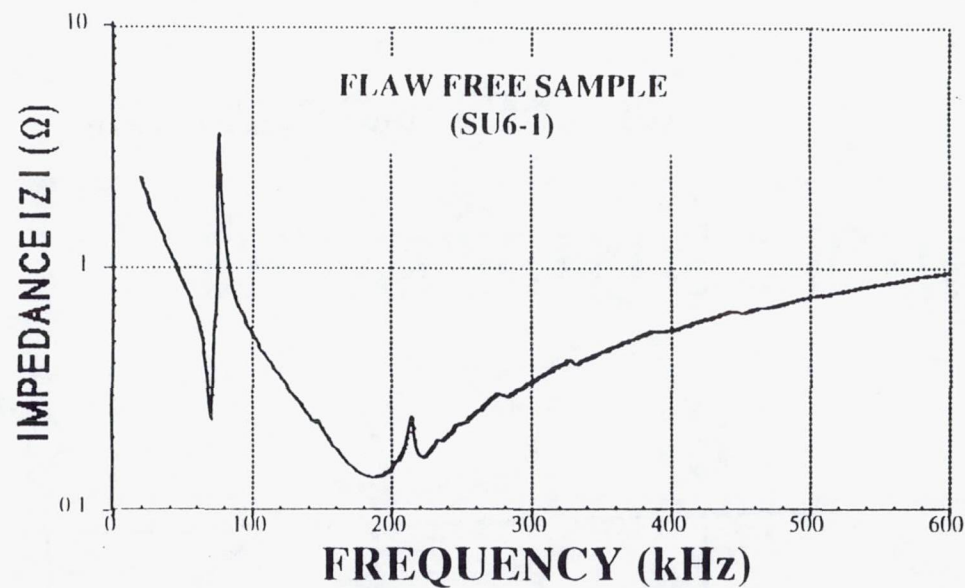
IMPEDANCE DIFFERENCES VS FREQUENCY
MEASURED AT 1kHz INTERVALS



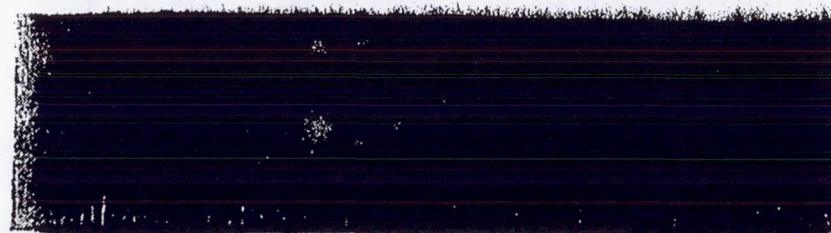
- Length 20mm
- Diameter 6.2mm
- 150 Platinum Electrode Layers Spaced at 0.115mm
- Maximum Voltage 150V
- Maximum Stroke 18.5 μ m

PMN ELECTROSTRICTIVE MULTILAYER ACTUATOR*

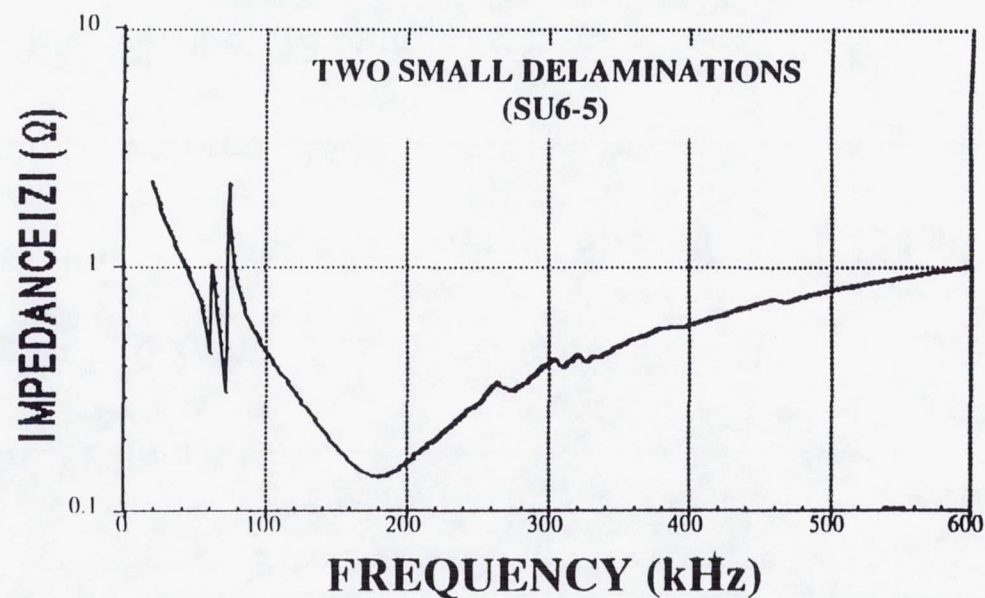
* AVX CERAMICS, MYRTLE BEACH, S.C.



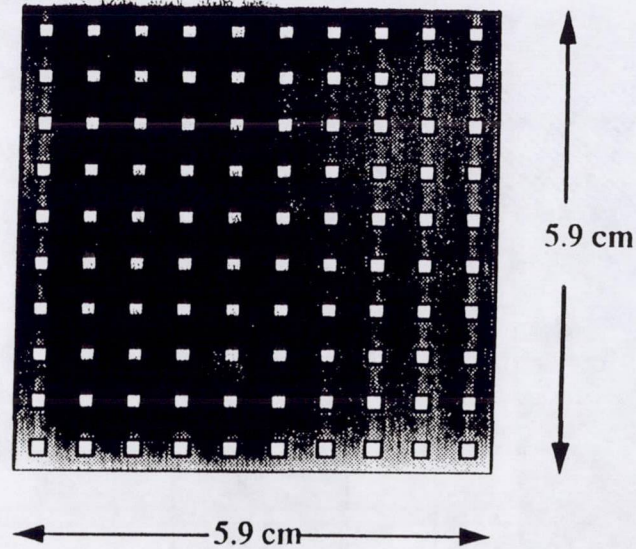
ELECTROSTRICTIVE ACTUATOR FREQUENCY RESPONSES (with 35V DC BIAS APPLIED)



Small Delamination in Sample SU6-3



Layout of Active Components



Cross Section of Actuator Row

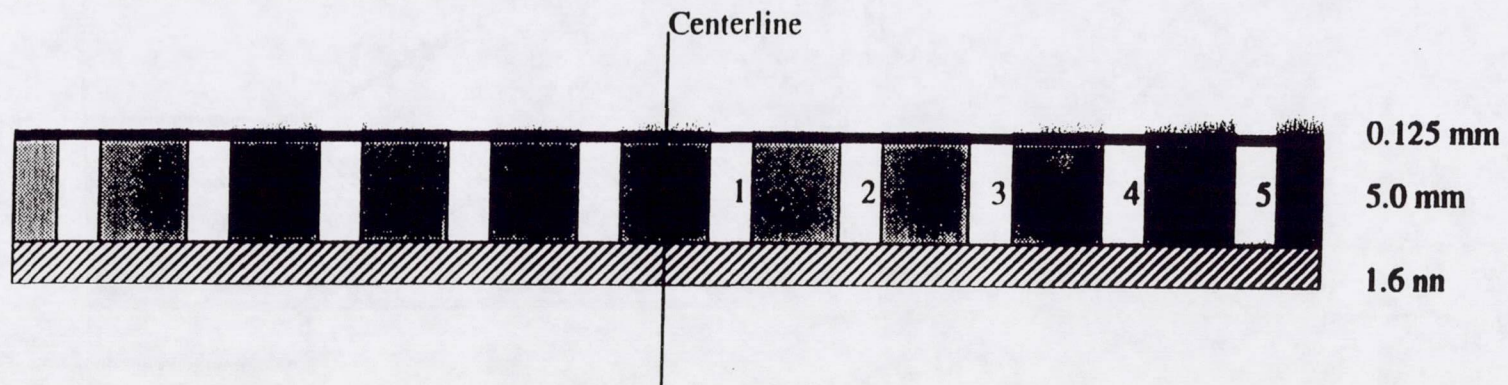


FIGURE 1a - Layout of Actuators and Composite Plate

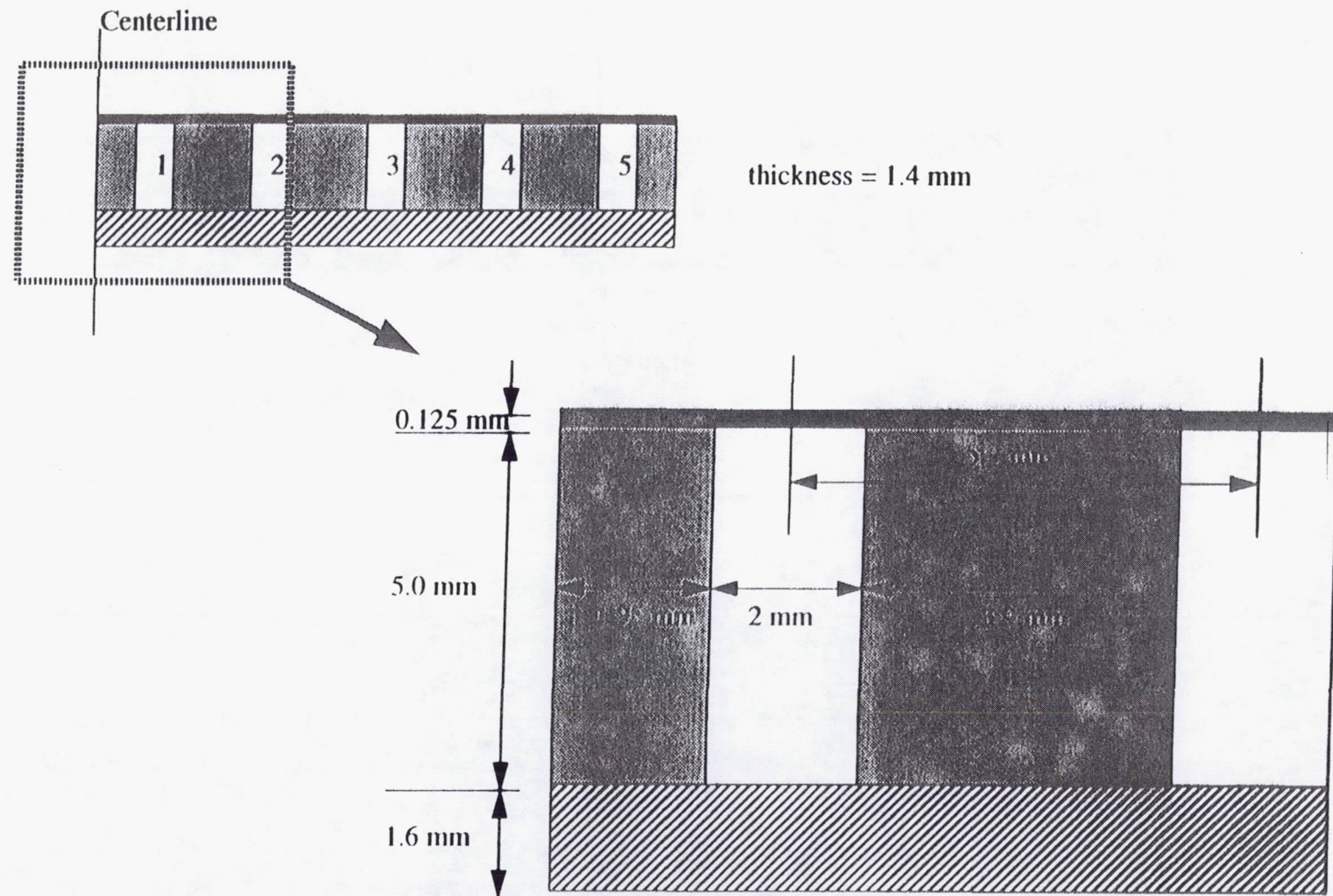
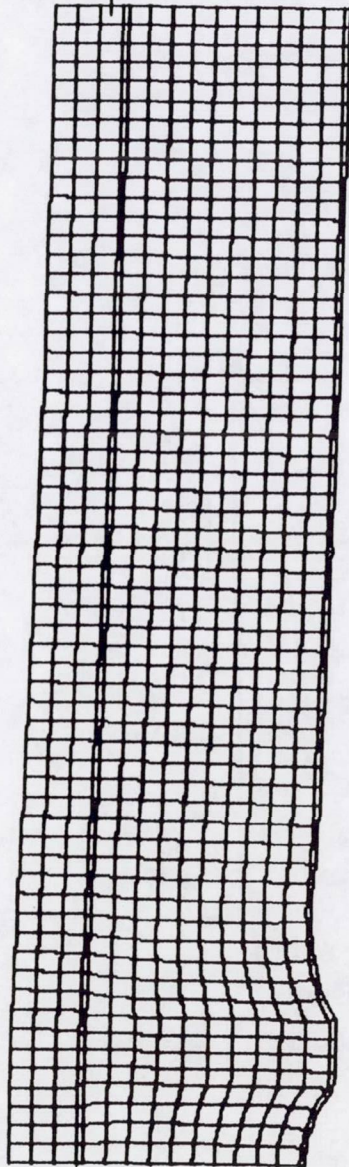
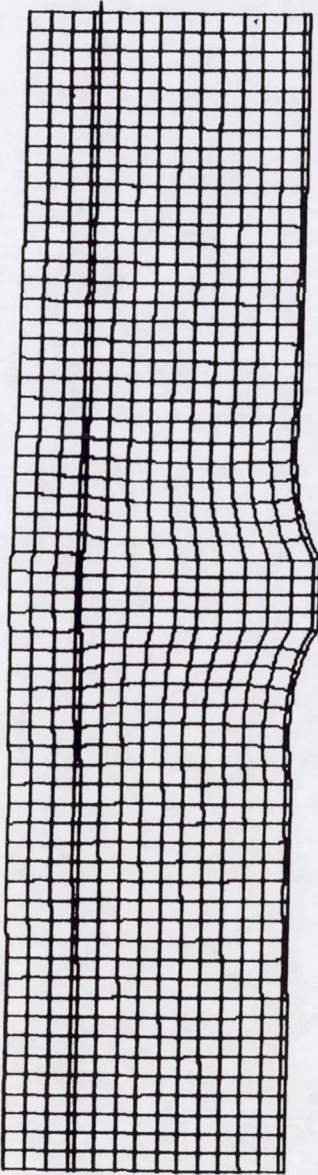
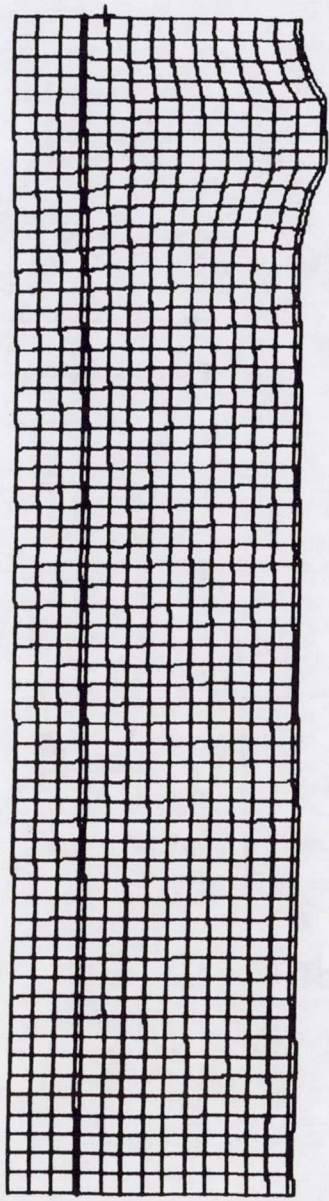
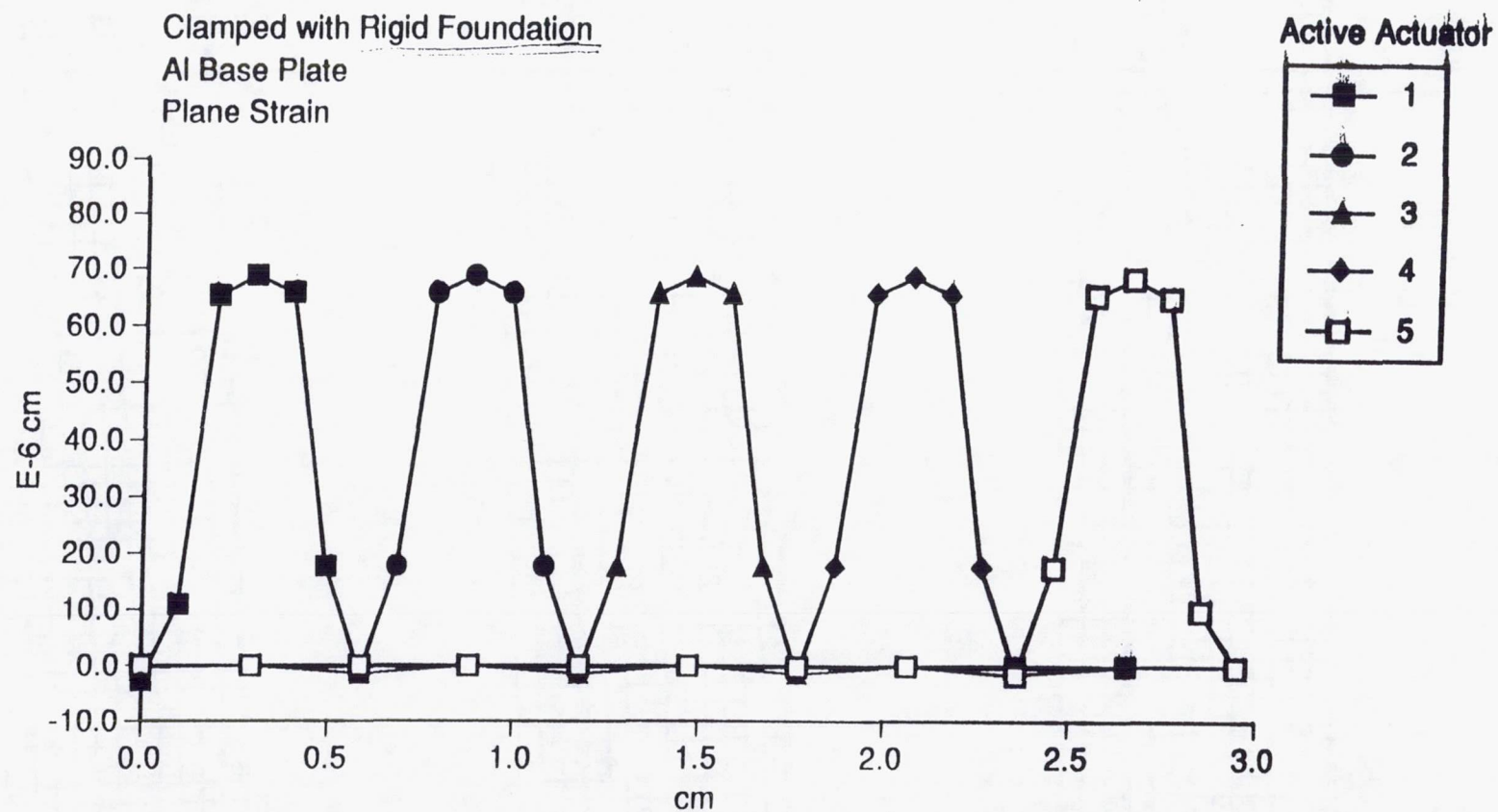
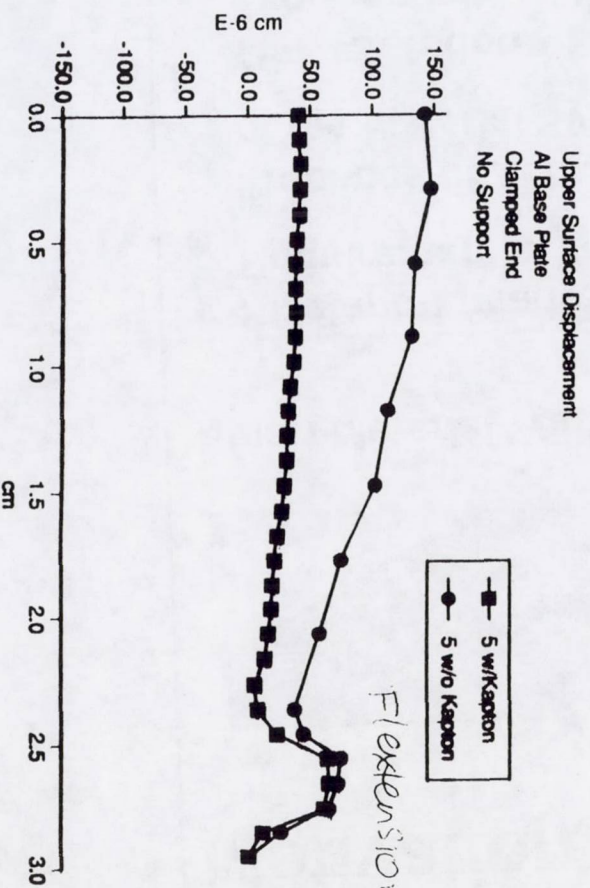
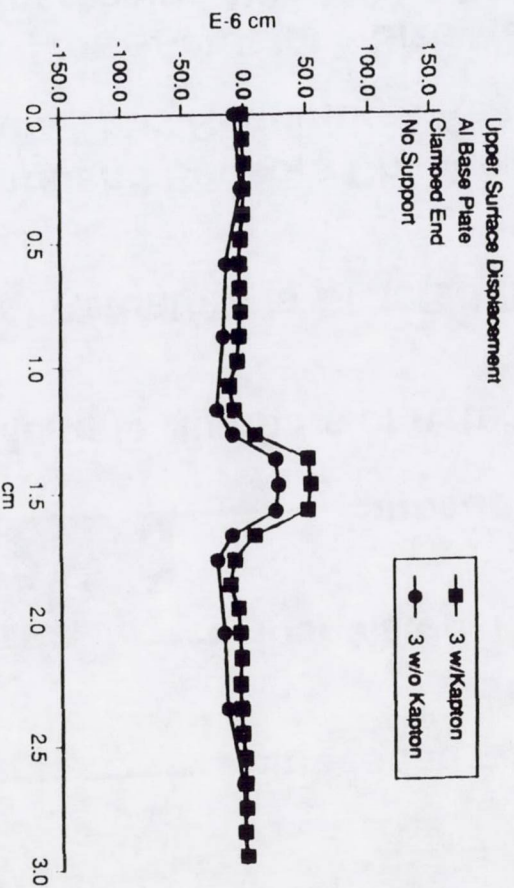
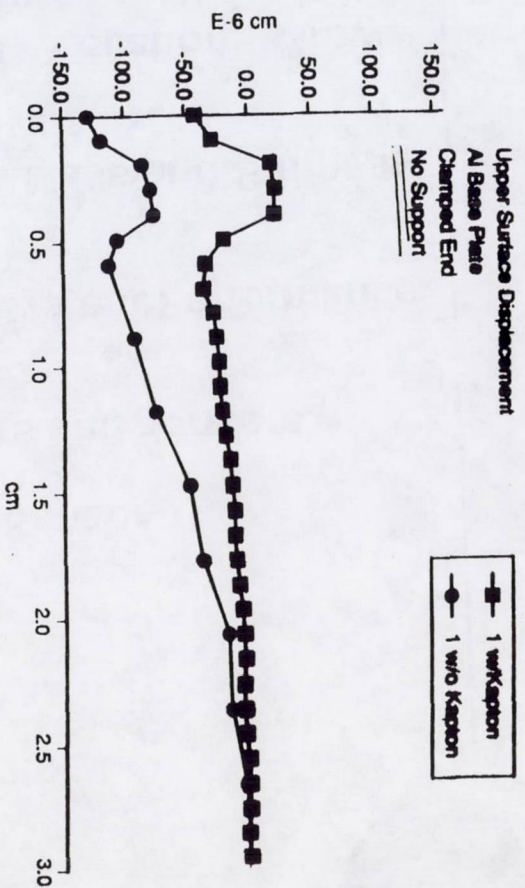


FIGURE 1b - Dimensions of Section Modeled in Finite Element Analysis



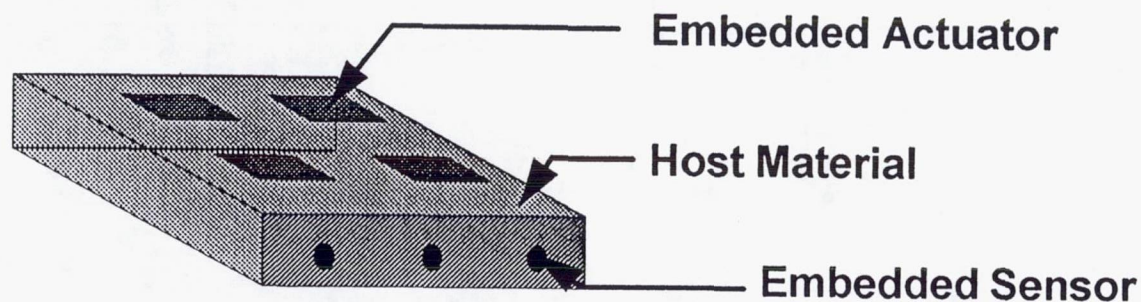




Flexional response



Motivation

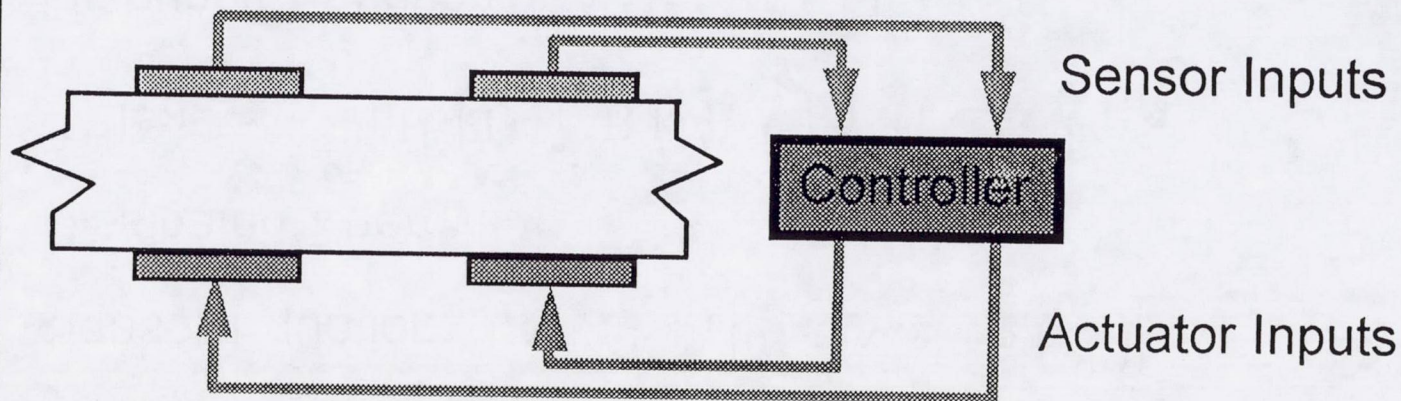


Smart Material With Multiple Numbers of Actuators and Sensors.

- **Size and Location of Actuators is Dictated By System Performance Requirements.**
- **Presence of Actuators and Sensors Change the Mass and Stiffness of the Material System Thus Requiring a Reanalysis.**
- **The Solution Set for Actuator Size and Location Grows Exponentially With Increasing Number of Actuators.**
- **Objective Function May Be Discontinuous.**



Global Control



Control Law: $\mathbf{u} = -\mathbf{K} \mathbf{x}$

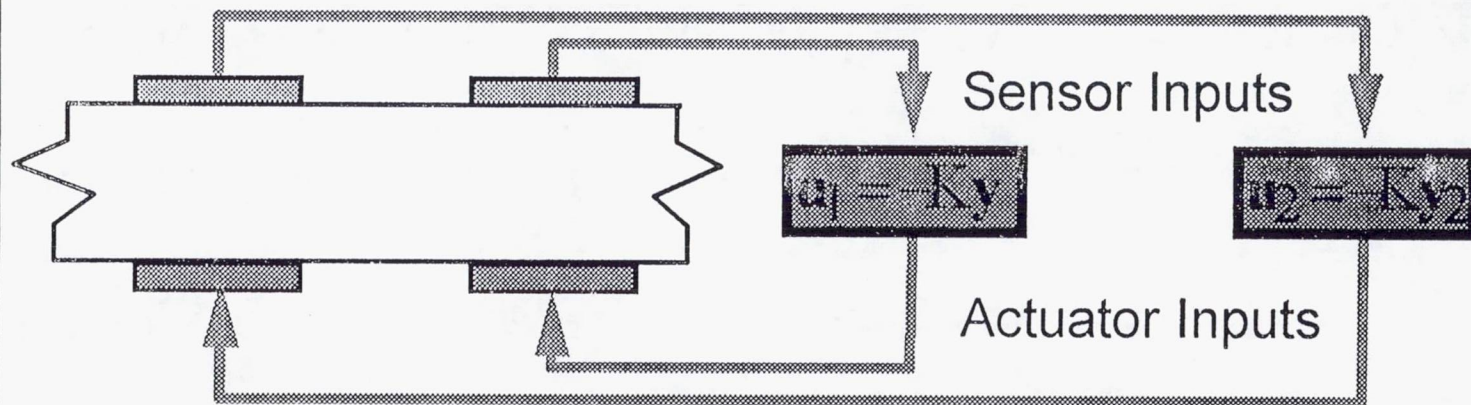
Minimize Cost: $J_1 = \int_0^{\infty} [\mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{u}^T \mathbf{R} \mathbf{u}] dt = \mathbf{x}_0^T \mathbf{S} \mathbf{x}_0$

$\mathbf{K} = \mathbf{R}^{-1} \mathbf{B}^T \mathbf{S}$ where $\mathbf{S}$ satisfies $\mathbf{A}^T \mathbf{S} + \mathbf{S} \mathbf{A} - \mathbf{S} \mathbf{B} \mathbf{R}^{-1} \mathbf{B}^T \mathbf{S} + \mathbf{Q} = 0$

Performance Metric: $J_1 = \min \text{trace}(\mathbf{S})$



Local Control



Sensor Equation: $y_r = K_{sen} \begin{bmatrix} 0 & \phi'_i(x_{r2}) - \phi'_i(x_{r1}) \end{bmatrix} x$

Dissipated Energy:

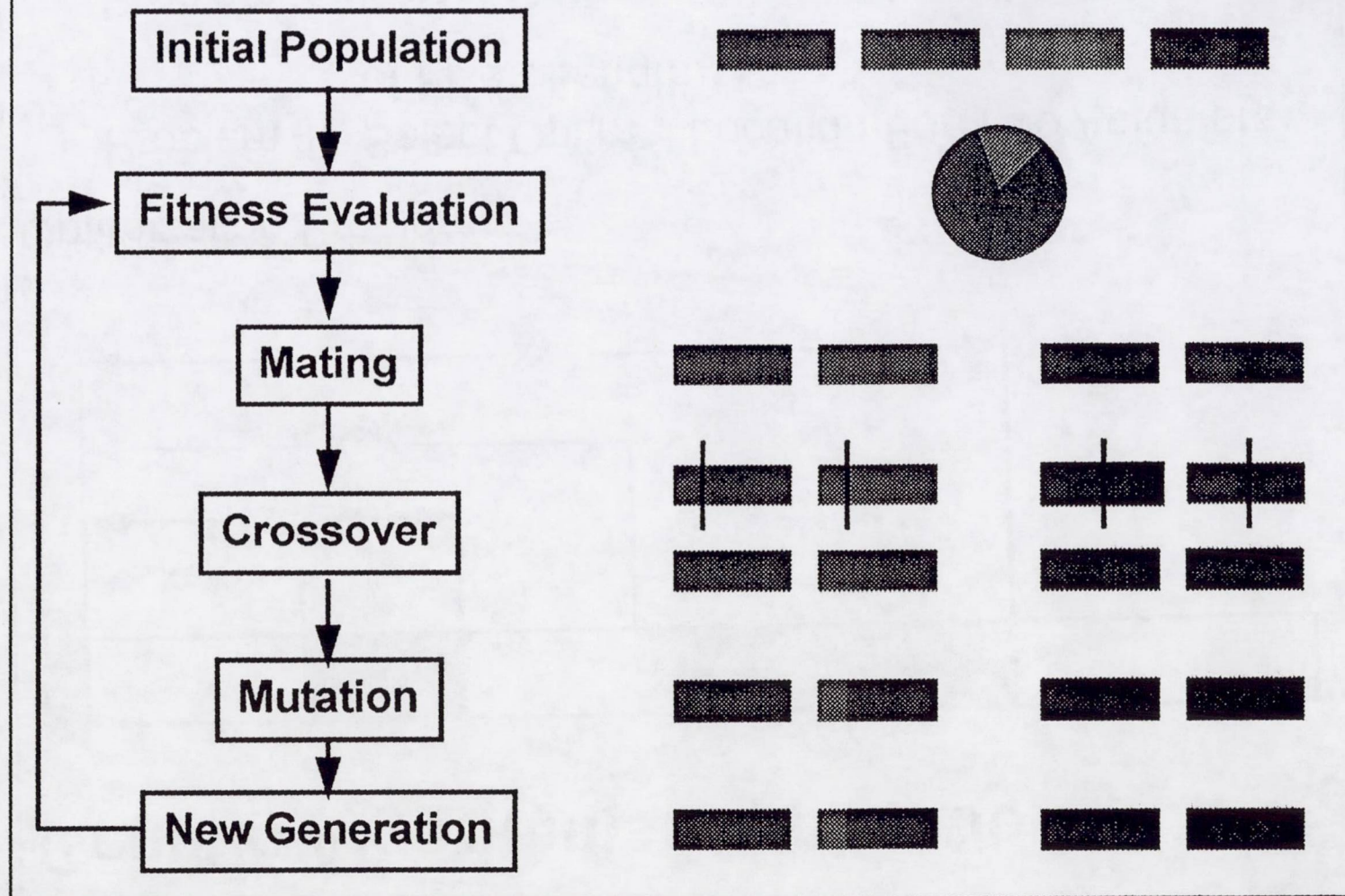
$$E_d = - \int_0^{\infty} \dot{\eta}^T (D + B K B^T) \dot{\eta} dt = x_0^T P x$$

Lyapunov Equation: $A_c^T P + P A_c + \Gamma =$

Performance Metric: $J_2 = \max \text{trace}(P)$

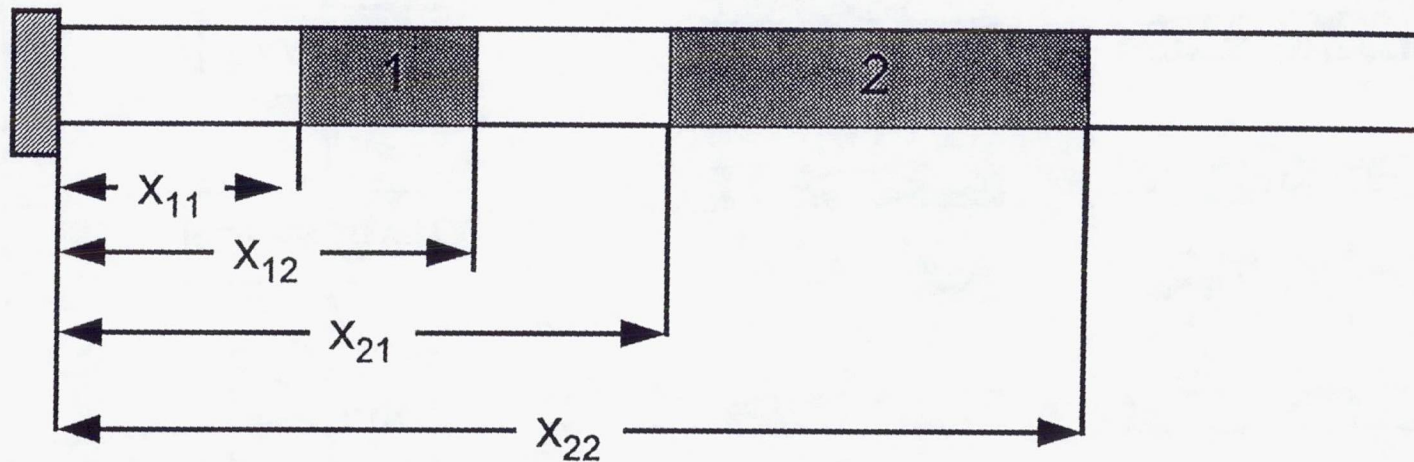


Genetic Algorithms: Flow Chart





Genetic Algorithms: Application



Optimization Problems:

Problem 1: Select Optimal Location For Two Actuators of Fixed Length.

Problem 2: Select Optimal Size and Location For Two Actuators



Fixed Length Actuators

Beam Discretized Into 64 Elements

Design Parameters: x_{11} and x_{21}

Design Parameters Encoded As a 12 Bit String

Parameter Constraints:

$$1 \leq x_{11} \leq 57 \quad (x_{12} = x_{11} + 4) \leq 61$$

$$x_{12} \leq x_{21} \leq 61 \quad (x_{22} = x_{21} + 4) \leq 65$$

Total Possible Solutions: $\sum_{n=1}^{57} n = 1653$

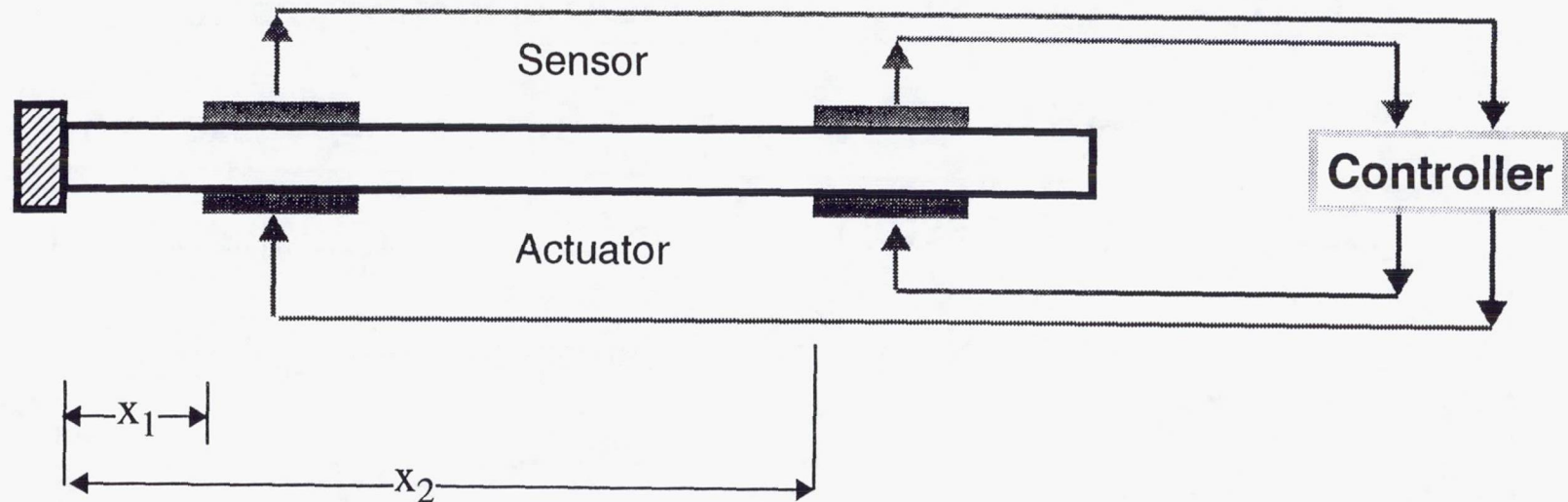
Population Size: 6

Crossover Rate: 80%

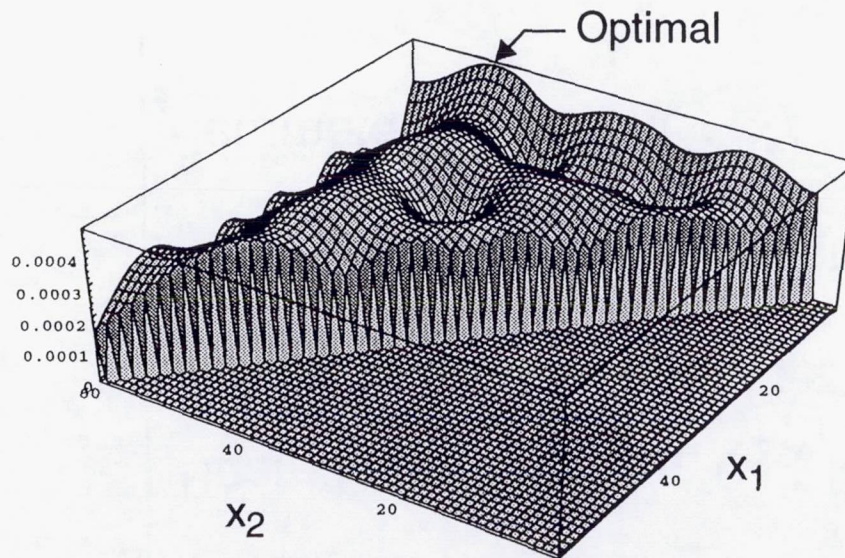
Generations: 40

Mutation Rate: 2%

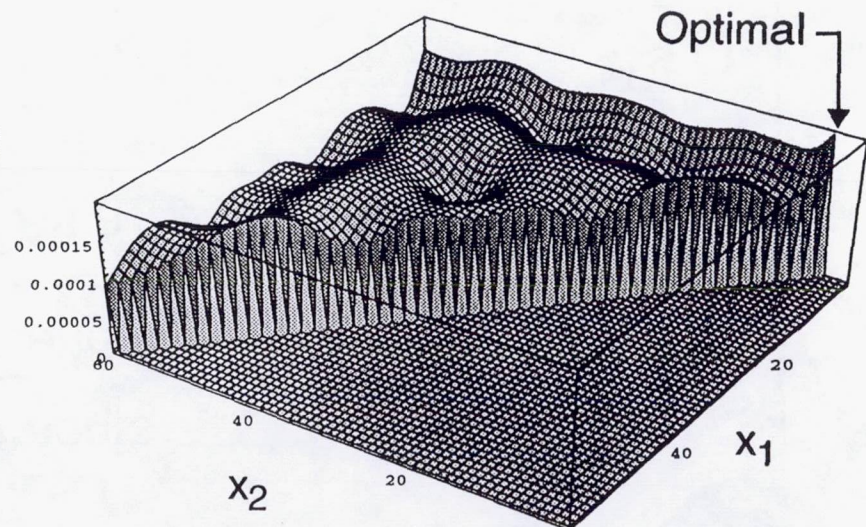
OPTIMAL ACTUATOR PLACEMENT FOR GLOBAL CONTROL



80

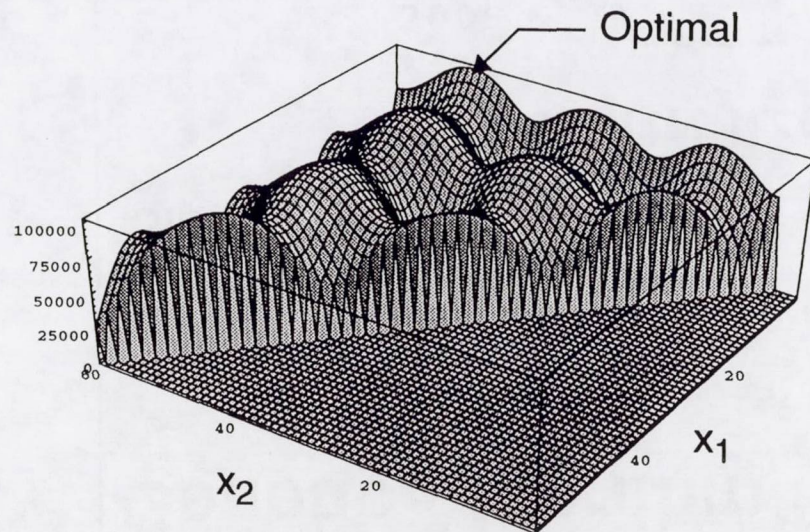
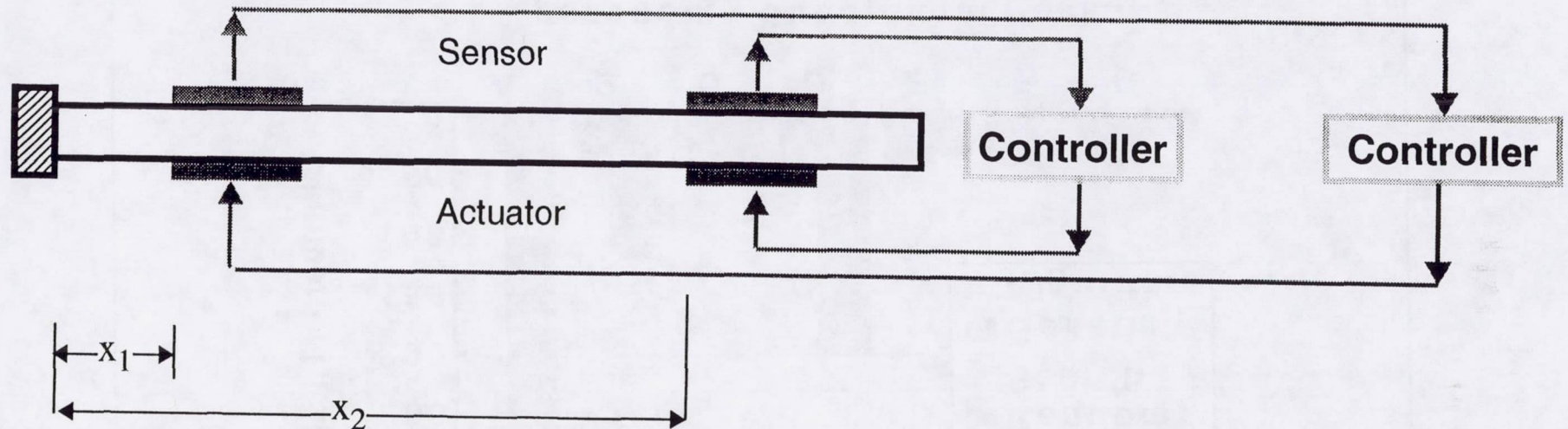


Actuator Mass and Stiffening Neglected

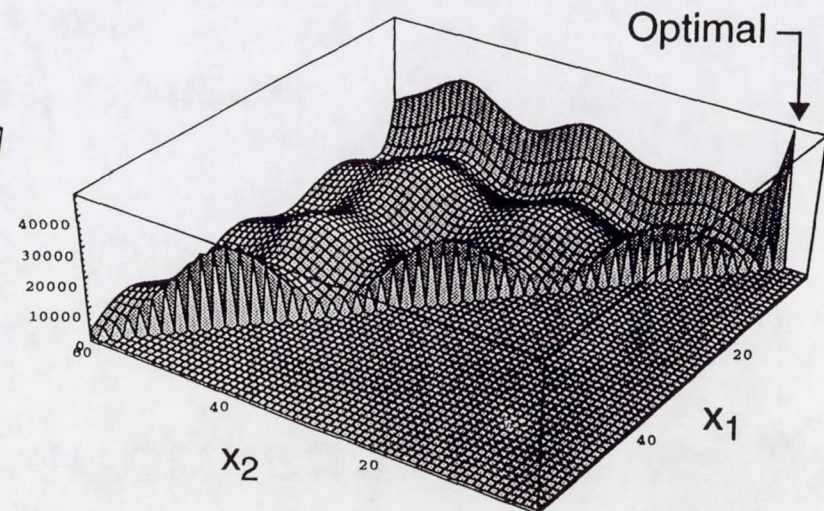


Significant Actuator Mass and Stiffening

OPTIMAL ACTUATOR PLACEMENT FOR LOCAL CONTROL



Actuator Mass and Stiffening Neglected

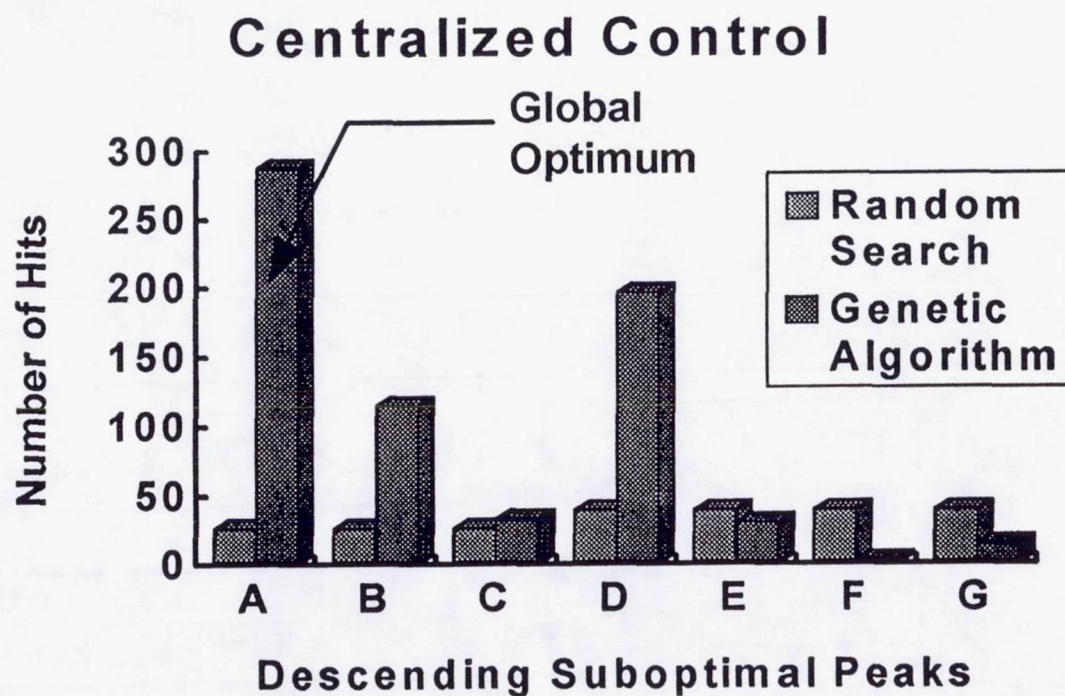


Significant Actuator Mass and Stiffening



Genetic Algorithm Performance

Population Size:	6	Crossover Rate:	80%
Generations:	40	Mutation Rate:	2%
Simulations:	30		





Variable Length Actuators

Beam Discretized Into 64 Elements

Design Parameters: x_{11} , x_{12} , x_{21} and x_{22}

Design Parameters Encoded As a 24 Bit String

Parameter Constraints: $1 \leq x_{11} \leq 63$ $x_{11} + 1 \leq x_{12} \leq 64$
 $x_{12} \leq x_{21} \leq 64$ $x_{21} + 1 \leq x_{22} \leq 65$

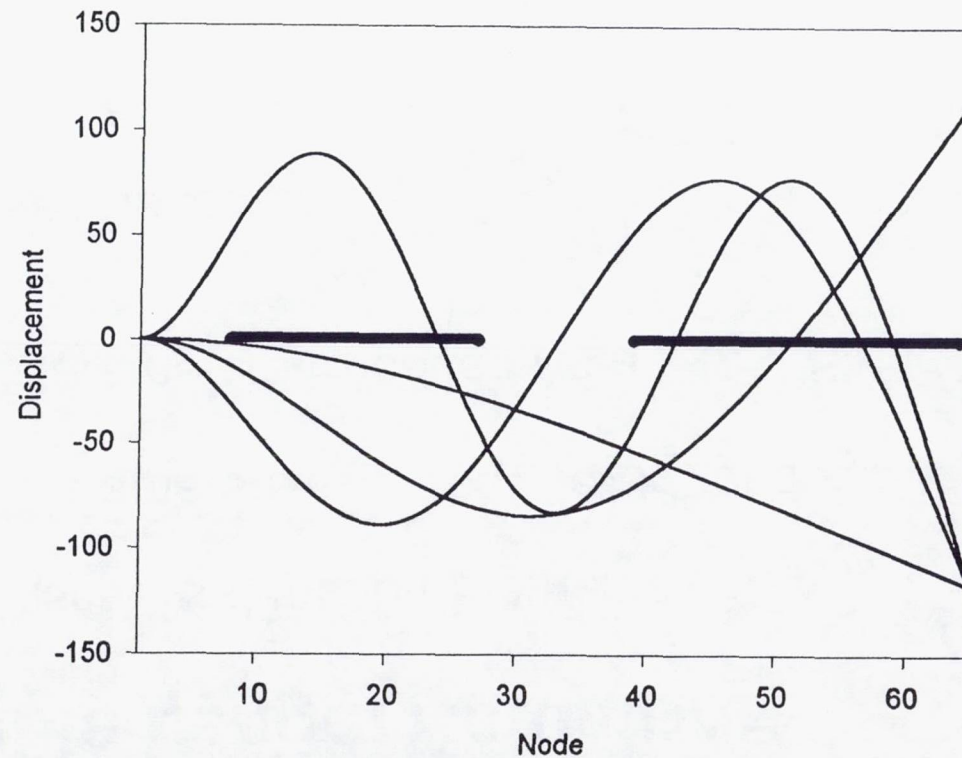
Total Possible Solutions: $\sum_{i=1}^{63} i \cdot \sum_{j=1}^{64-i} j = 720,720$

Population Size:	20	Crossover Rate:	80%
Generations:	40	Mutation Rate:	2%



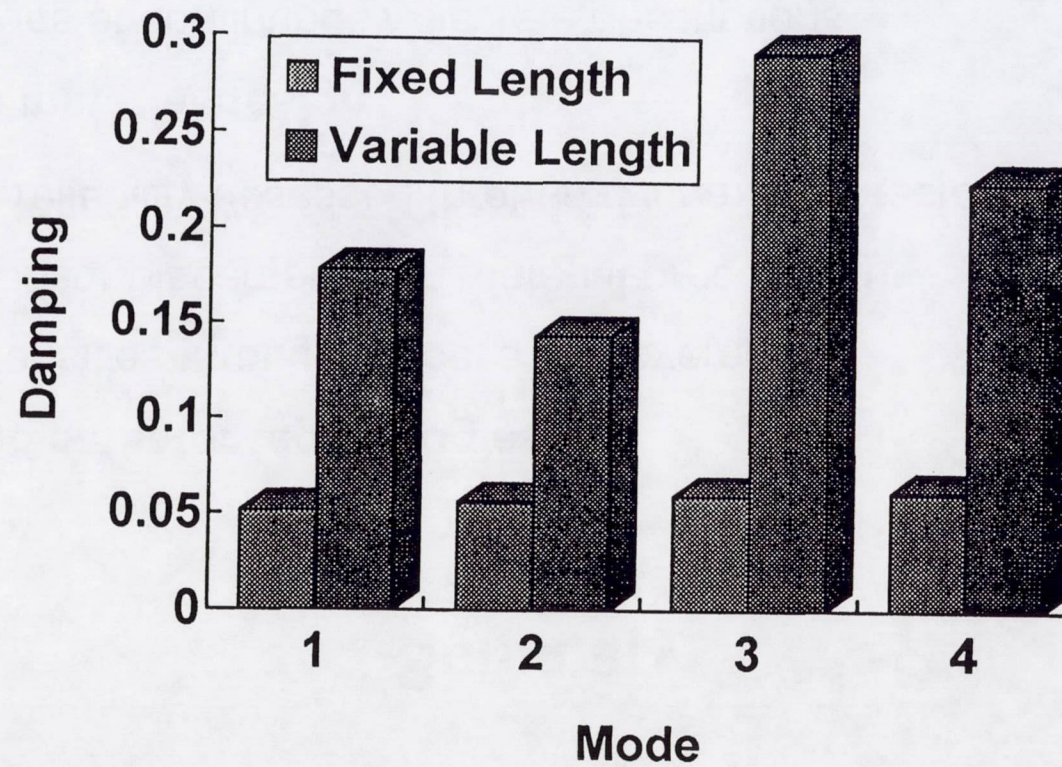
Variable Length Actuator

Optimal Actuator Size and Location





Increase in Damping



Summary

Sensor and actuator technologies

- Higher densities through process improvements
- Merge sensor placement with material processing
- Actuator reliability assessed through dynamic characteristics

Integrated material design

- Advantages of continuous / discrete descriptions
- Combinatorially driven problem framed in terms of performance
- Role for directed search algorithms in material design

Smart Materials: The Structures Division Program at Wright Laboratory

Capt Kimberly B. Demoret
WL/FIBG

MISSION

SMART STRUCTURES

OBJECTIVE

- Develop and transition flight vehicle structures which can sense their operating environments, process the resulting information, and take action based on that information.

APPROACH

- Conduct high-payoff research and team with other agencies to test/demonstrate smart structures technologies

IMPACT

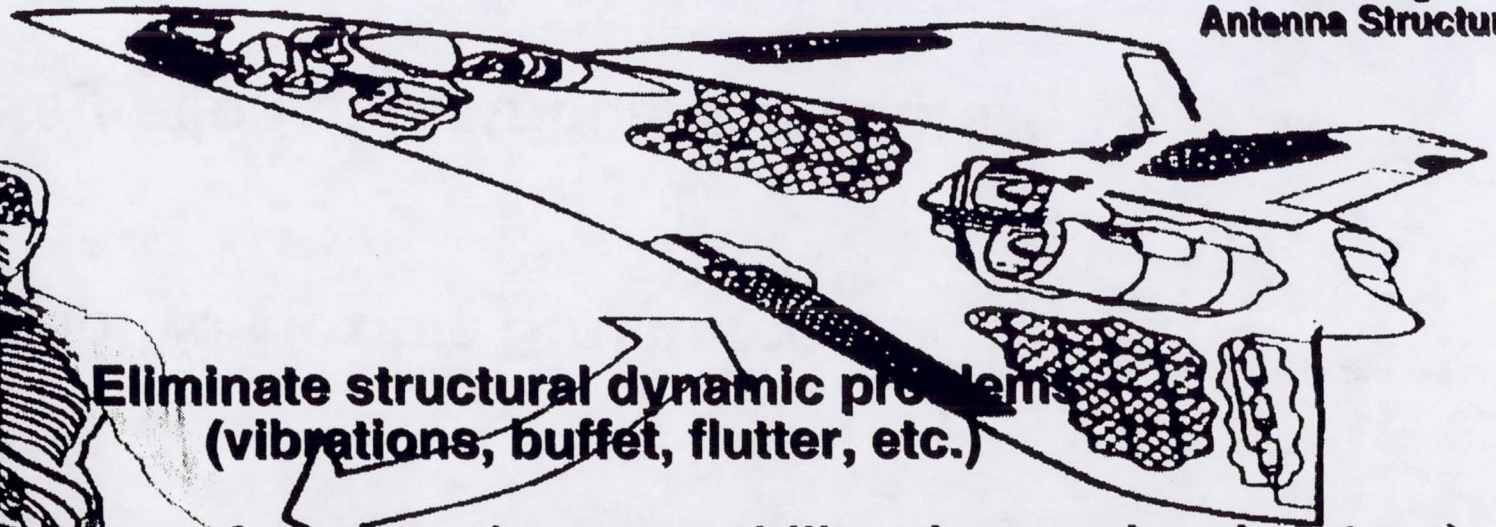
- Reduce cost
- Improve performance

CURRENT FOCUS AND VISION

SMART STRUCTURES

**Structural
Integrity
Monitoring**

**Conformal Load
Bearing
Antenna Structure**



**Eliminate structural dynamic problems
(vibrations, buffet, flutter, etc.)**

**Enhance vehicle performance (maneuverability, drag, radar signature)
while eliminating the need for discrete control surfaces**

**Employ multi-function structural components to
monitor fatigue, corrosion, battle damage,
decrease TOGW**

**Piezoelectric
Vibration
Suppression
Control - Structures
Interaction**

**Adaptive
Flexible
Structures**

TABLE OF CONTENTS

SMART STRUCTURES

- **Background**
- **Vibration Suppression**
- **Adaptive Flexible Structures**
- **Integration of Distributed Sensors**

VIBRATION SUPPRESSION/CONTROLS - STRUCTURES INTERACTION

SMART STRUCTURES

OBJECTIVE

- Eliminate structural dynamic instabilities and fatigue damage due to vibration

APPROACH

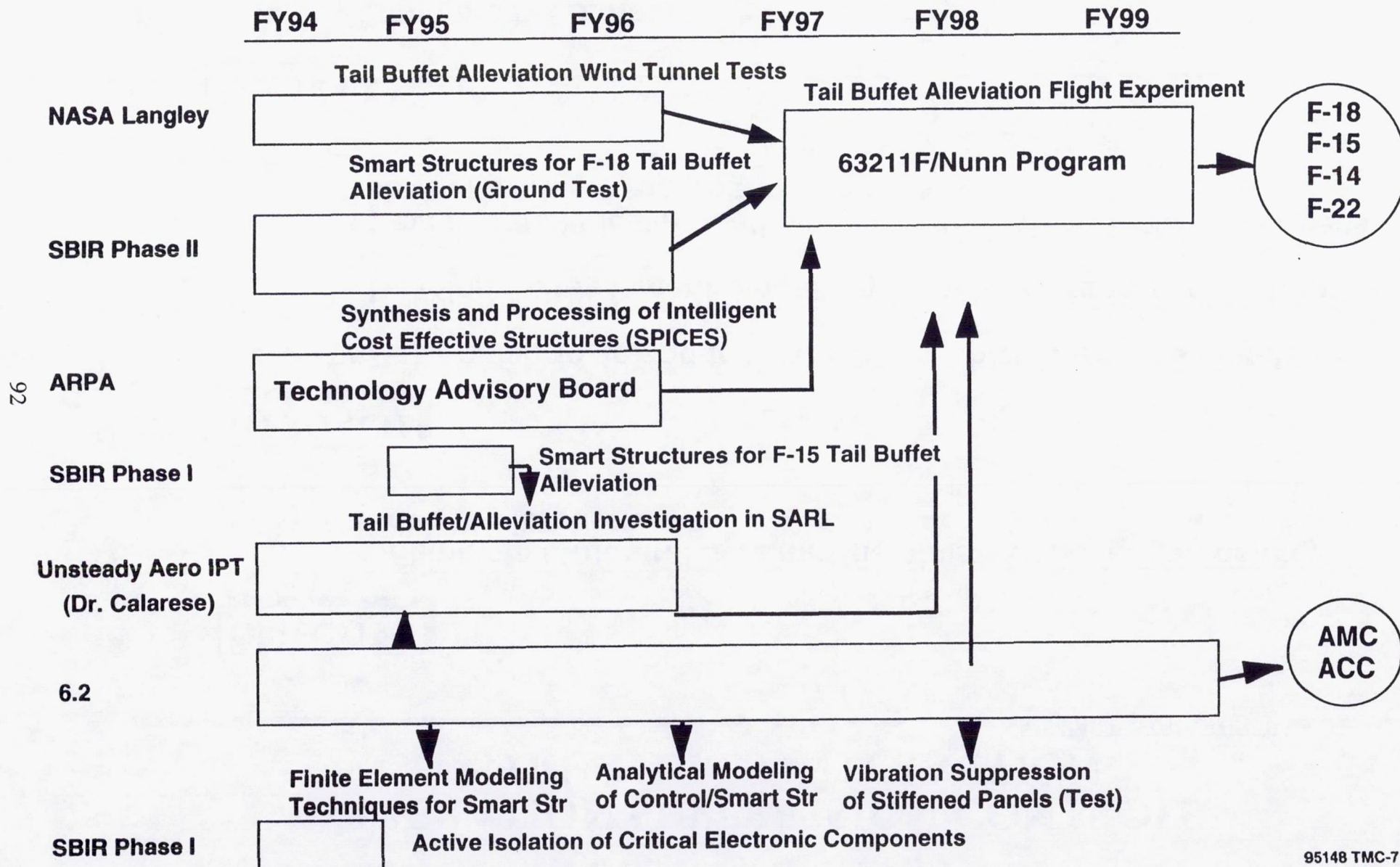
- Design, fabricate and test structures which suppress vibrations
- Develop finite element modelling techniques for smart structures
- Develop analytical modelling techniques which include feedback control systems for smart structures

IMPACT

- Eliminate tail buffet
- Eliminate wing/store flutter
- Isolate electronic components, etc, from forced vibration

VIBRATION SUPPRESSION/CONTROLS- STRUCTURES INTERACTION

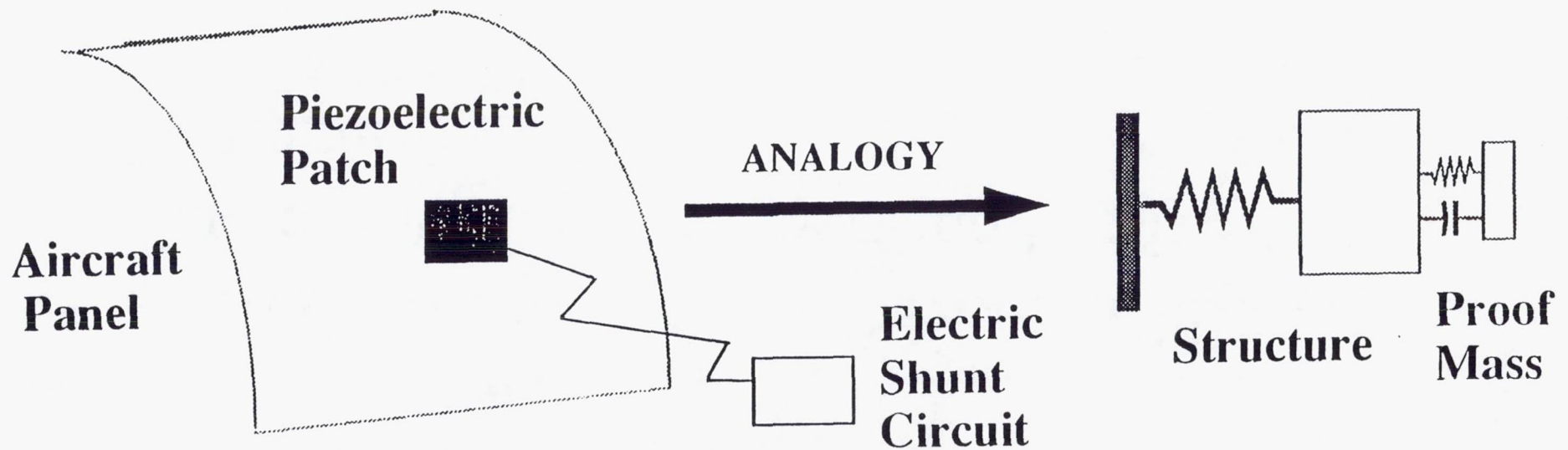
SMART STRUCTURES



Vibration Suppression Research (in- house)

- Piezoelectric Vibration Absorbers
- Piezoelectric Strain Mapping
- Analysis Techniques for Piezoelectrics, Active Constraining Layer and Passive Damping

Piezoelectric Vibration Absorbers

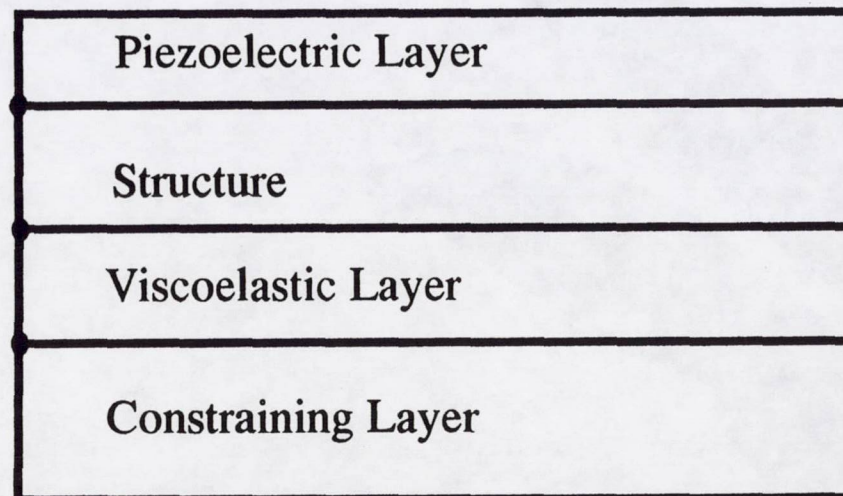


The piezoelectric patch transforms mechanical strain into electrical energy which is dissipated in a tuned shunt.

- ❑ **Importance:** Vibration absorber for plate and shell structures.
- ❑ **Uniqueness:** (1) Self-tuning (2) Multimodal
- ❑ **Results:** An order of magnitude reduction in strain.

Vibration Suppression Via Piezoelectric Actuators and Sensors and Constrained Layer Damping

- Actively controlled (piezoelectric) finite element
- Passive damping finite element (CLD)
- Control system design including robustness and stability
- Location and amount of damping treatment
- Simultaneous structure-control design
- Multiobjective optimization





Tail Buffet

- At high AOA, separated flow from LEX impinges on vertical tail
 - resulting fatigue damage has cost millions
- Tail Buffet Programs
 - F-18 Buffet: Phase II SBIR
 - NASA Langley tunnel tests
 - F-15 Buffet: Phase I SBIR
 - Wright Lab Unsteady Aerodynamics IPT

ADAPTIVE FLEXIBLE STRUCTURES

SMART STRUCTURES

OBJECTIVE

- Use smart structures to achieve maneuver performance, thus eliminating the need for discrete control surfaces while minimizing drag and signature

APPROACH

- Combine aeroelastic tailoring concepts with wing structure constructed of smart / actuating materials
 - Wing warping for maneuver
 - Camber shaping for aerodynamic performance and reduced drag

IMPACT

- Eliminate rolling tail/discrete control surfaces
- 30% TOGW reduction
- Reduce radar signature
- Reduce drag/increase range

ADAPTIVE FLEXIBLE STRUCTURES

SMART STRUCTURES

FY 94 FY95 FY96 FY97 FY98 FY99 FY00 FY01

ARPA

ARPA Adaptive/Smart
Wing Phase I Wind Tunnel Test

ARPA Adaptive/Smart Wing
Phase II Wind Tunnel Test

(FIB Tech Monitor)

(FIB Tech Monitor)

Adaptive Flexible Structures for Air
Vehicles (International Effort)

Nunn

Allied

SBIR

6.2

Camber Control
Using SMA

Contributions to
International Program

Aeroelastic
Tailoring for
Smart
Structures

63211F
Nunn &
Allied Funds

Smart Affordable Structures

Flight
Test

95148 TMC-6

Adaptive Flexible Structures

- Goal: Exploit smart materials to develop wings whose shape or stiffness varies in flight

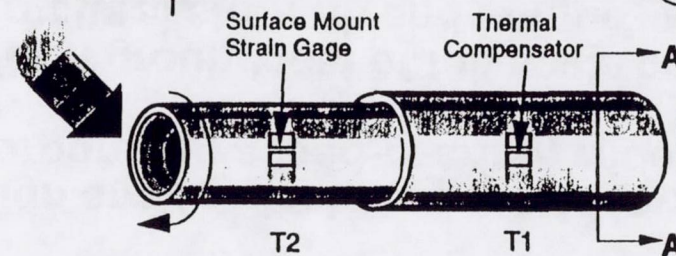
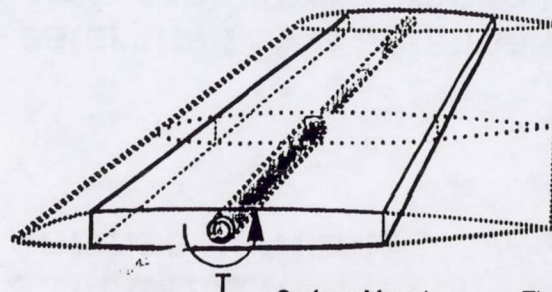
100

- Programs

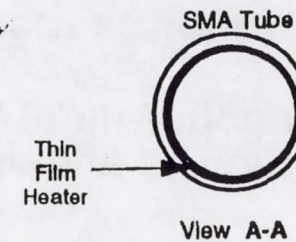
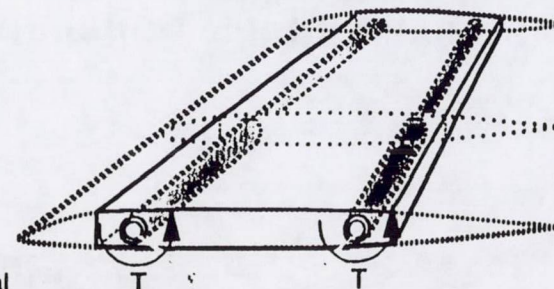
- Northrop Grumman Smart Wing Program
(ARPA funded; monitored at WL)
- Aeroelastic Tailoring for Smart Structures
(6.2 in-house research)
- SBIR Phase I : Camber Control Using SMAs

Wing Twist Actuation Concepts

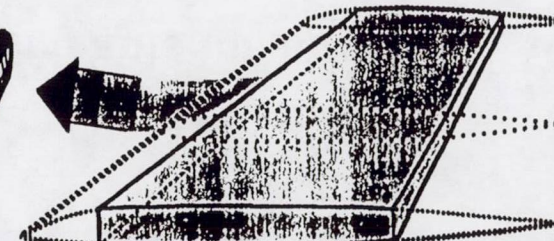
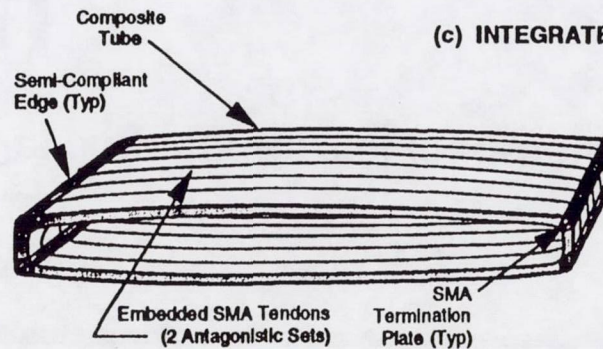
(a) NESTED TORQUE TUBES



(b) TWIN NESTED SMA TORQUE TUBES



(c) INTEGRATED SMA TORQUE BOX



SMART SKINS

OBJECTIVE

- Develop conformal load-bearing antenna structure

APPROACH

- Design and fabricate upper and lower fuselage structure incorporating a load-bearing, wide-band, multi-function antenna
- Perform ground test of full-scale component structure
 - Structural strength and fatigue
 - Antenna performance

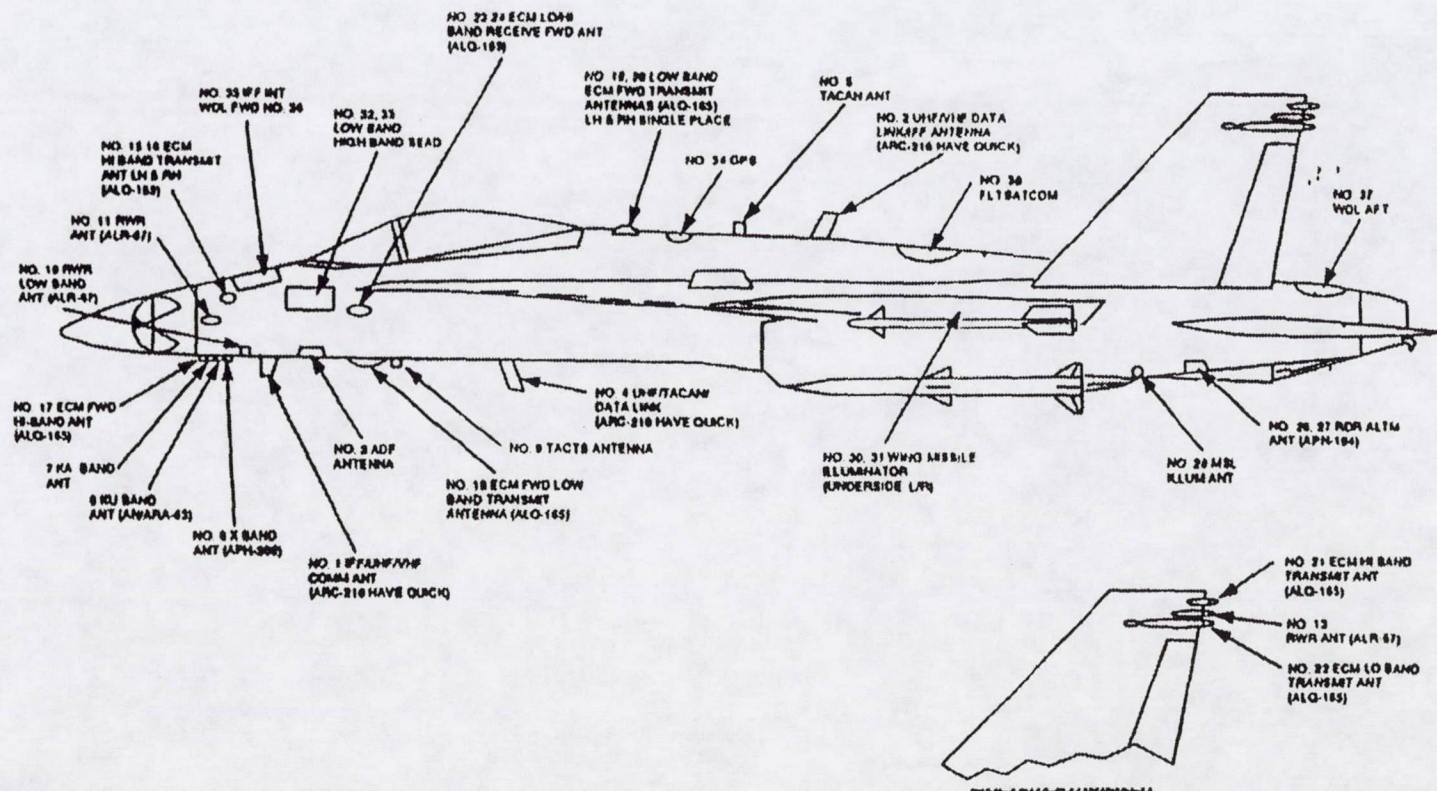
IMPACT

- Greater than 50% antenna installation weight savings
- Greater than 50% antenna manufacturing cost savings
- Better antenna performance
 - Greater than 100% range improvement
 - Coverage enhancements
 - New capabilities, such as low frequency threat warning
 - Lower signature and drag characteristics

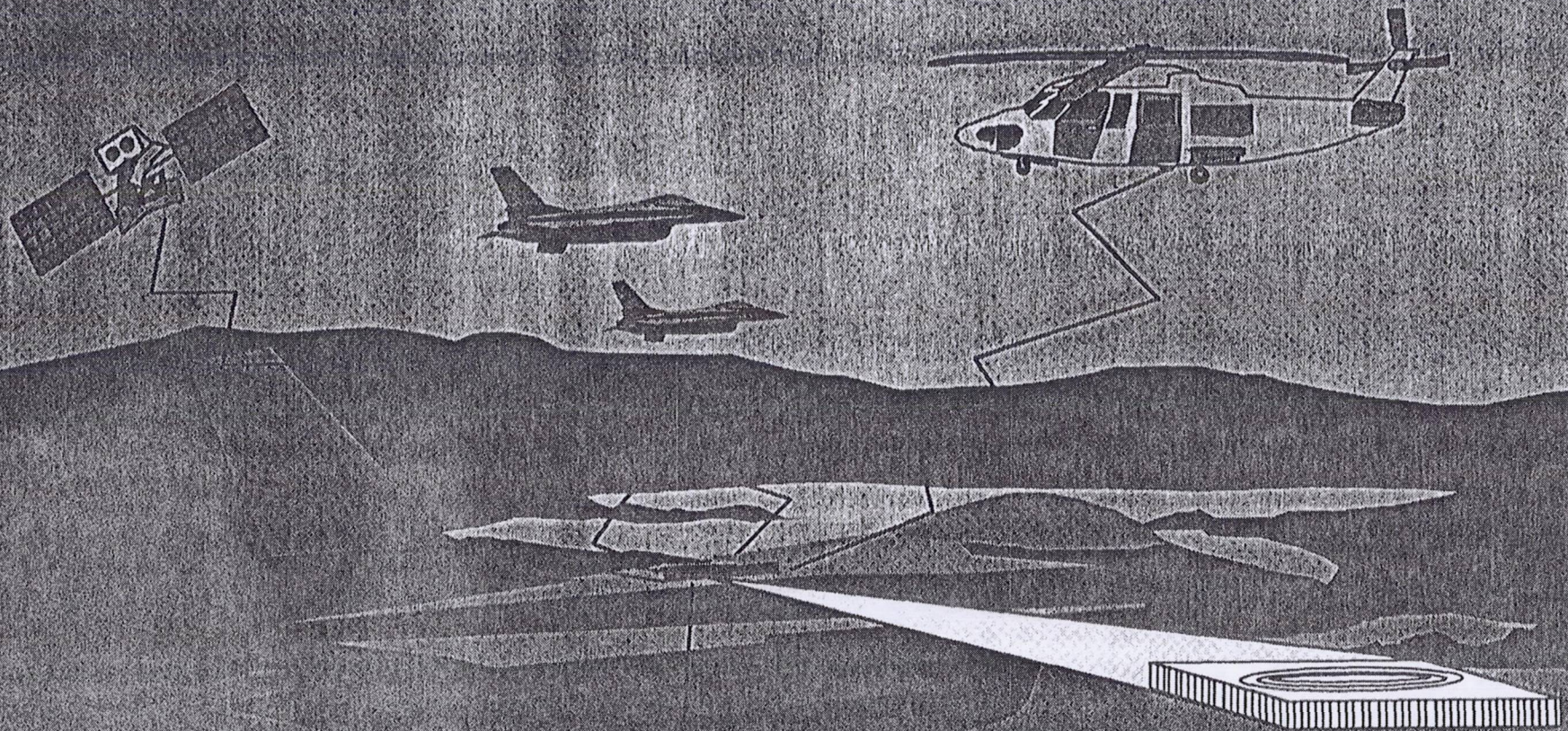
THE MILITARY ANTENNA PROLIFERATION PROBLEM

SMART STRUCTURES

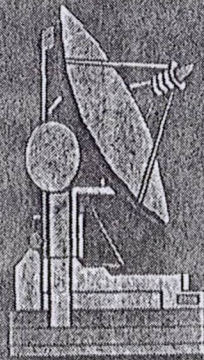
F/A-18 antenna system requires 66 apertures at 37 sites



SMART-SKIN STRUCTURE TECHNOLOGY DEMONSTRATION

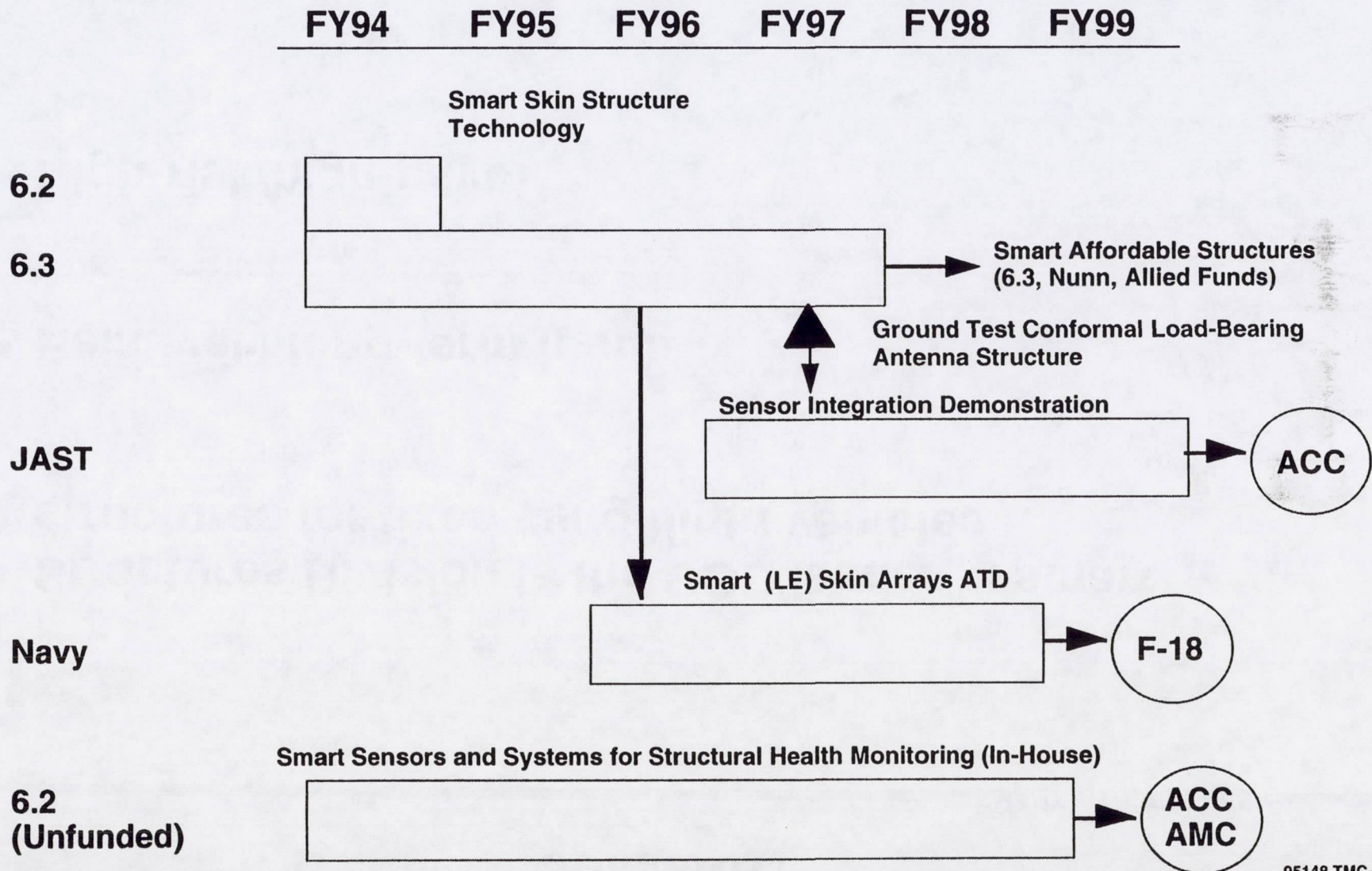


**CONFORMAL LOADBEARING
MULTIFUNCTION ANTENNA
STRUCTURE**



STRUCTURAL INTEGRATION OF DISTRIBUTED SENSORS

SMART STRUCTURES



SUMMARY

SMART STRUCTURES

- **Structures Division is the DOD leader in smart structures for fixed-wing flight vehicles**
- **Relatively long-term focus**
- **High-risk/high-payoff**

OFFICE OF NAVAL RESEARCH
ADAPTIVE STRUCTURES WITH ACTIVE MATERIALS

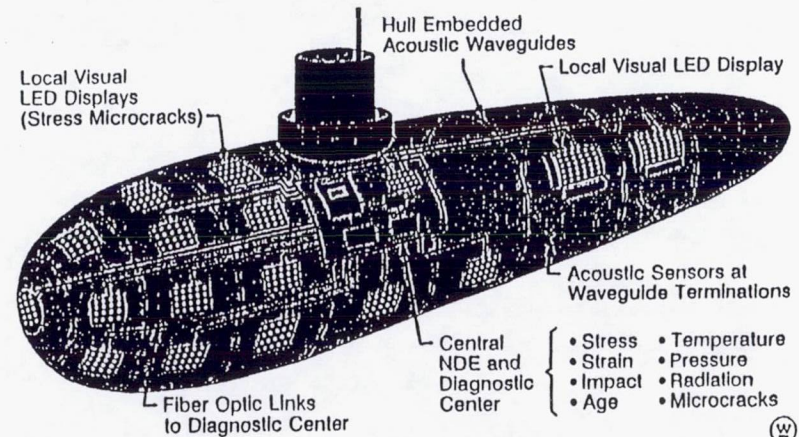
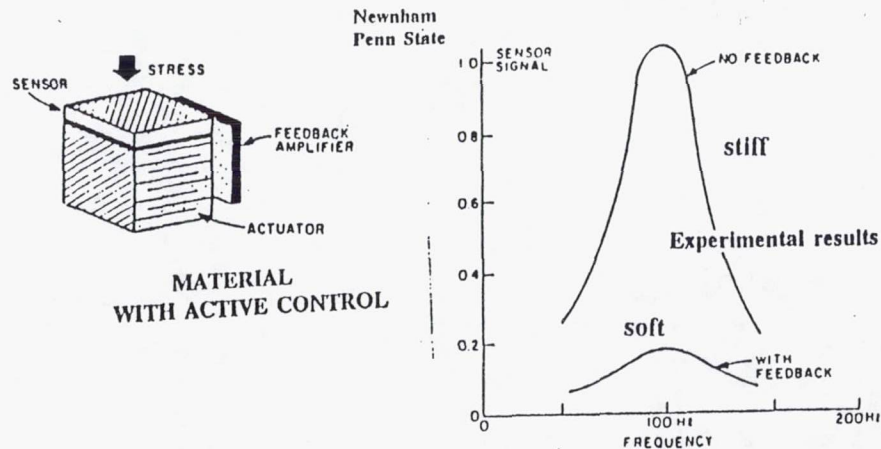


ROSHDY G. S. BARSOU

ACTIVE MATERIALS AND ADAPTIVE STRUCTURES

"SMART STRUCTURES"

FEEDBACK CONTROL OF ELASTIC COMPLIANCE.



OBJECTIVES:

- o UNDERSTAND MECHANICAL BEHAVIOR OF SMART MATERIALS IN VARIOUS ENVIRONMENTS
- o TAILOR NEW ACTIVE MATERIALS AND HYBRIDS.

APPROACH

- o MULTI-DISCIPLINARY, MECHANICS AND MATERIALS
- o NEW ACTIVE MATERIALS WITH LARGE STRAIN AND HIGH FREQUENCY
- o INTEGRATION OF SENSORS AND ACTUATORS
- o INVESTIGATION OF MECHANICAL BEHAVIOR (FATIGUE AND FRACTURE) IN COUPLED FIELDS

IMPACT:

- o NEW SENSORS WITH HIGH SENSITIVITY AND ACTUATORS WITH HIGH EFFICIENCY
- o ACCURATE CONTROL OF ACTIVE MATERIALS RESPONSE WITH HIGH FIDELITY AND RELIABILITY
- o ACTIVE CONTROL OF STRUCTURAL ACOUSTIC RADIATION AND SCATTERING.
- o DAMAGE SENSING AND CONTROL
- o VIBRATION CONTROL

R. Barsoum ONR 334 - barsour@onrhq.onr.navy.mil

W. Smith ONR 332 - smithw@onrhq.onr.navy.mil

ACTIVE MATERIALS/ADAPTIVE STRUCTURES

**APPLICATION : VIBRATION CONTROL AND STRUCTURAL ACOUSTIC
CONTROL AND REAL-TIME TARGETING**

BASIC TECHNICAL ISSUE

- Large Strains and High Frequency
- High force actuators

TYPE : ELECTRO-MAGNETO AND THERMO-MECHANICAL

SCIENCE ISSUES

- new electrostrictive and magnetostrictive materials
- Faster response
- Phase transformation
- Fatigue and Fracture
- Constitutive modeling and micro-mechanics of active materials
- Interfacial failure mechanisms of host material
- Novel actuators
- Mechanics of Hybrid active materials
- Structural response and adaptivity

ADAPTIVE STRUCTURES WITH ACTIVE MATERIALS

URI (Penn State) MATERIALS

ONR-ARI

NRL-ARI

URI "Materials for Adaptive Structural Control"
E. Cross - Penn. State

Materials Focus

Sensor / Actuator Development

Piezoelectricity in Field Biased Electronics

Processing Studies

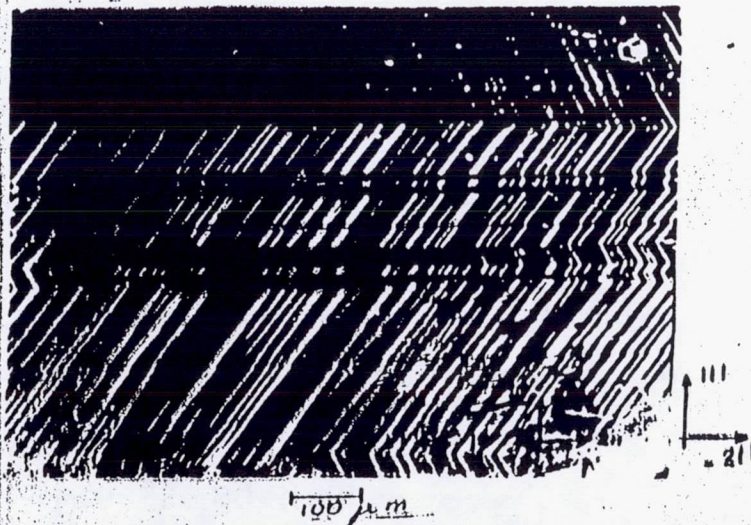
Materials for Integrated Sensor/Actuator Combinations

III

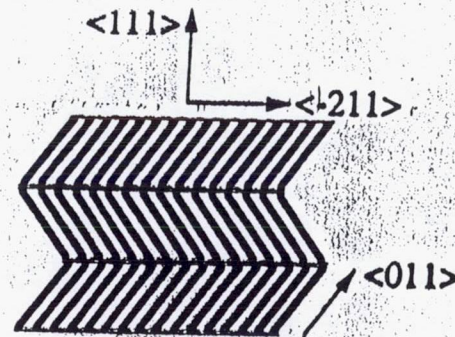
Reliability and Actuator studies

MECHANICS OF MAGNETOSTRICTION EFFECT AND PREDICTION OF DOMAIN STRUCTURE

High Resolution Microscopy
(Lord / UK)



PREDICTION OF MIN. ENERGY CONFIGURATIONS
(R. James U. of Minn.)

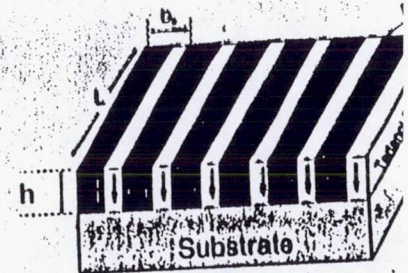
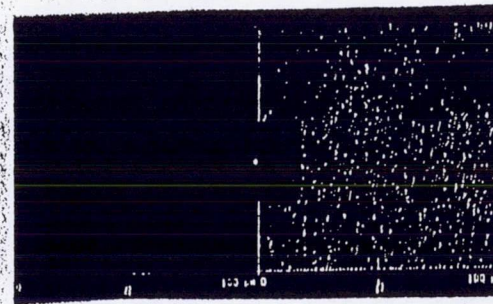


TRANSITION TO ARPA
MAGNETICALLY DRIVEN PHASE TRANSFORMATIONS

NEW MAGNETIC SHAPE MEMORY MATERIALS

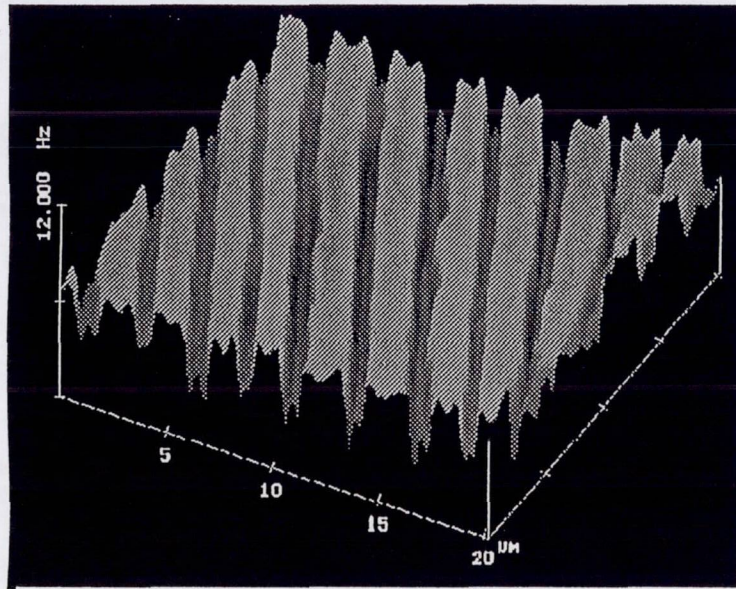
HIGH PERFORMANCE MAGNETO FERROELASTIC
ACTUATORS

JOINT EFFORT U. OF MINN. AND U. OF MD

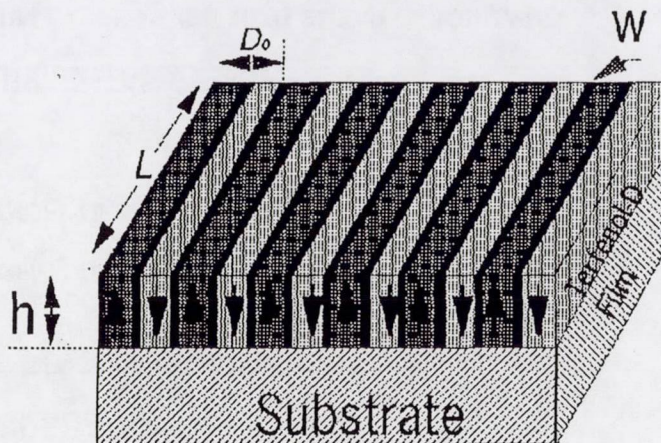


COMPOSITES AND THIN FILMS
(M. Wuttig U. MD)

AMORPHOUS THIN FILM TERFENOL POLYDOMAIN PHASE
ONR-N00014-93-10506, MANFRED WUTTIG, PI / U. MD

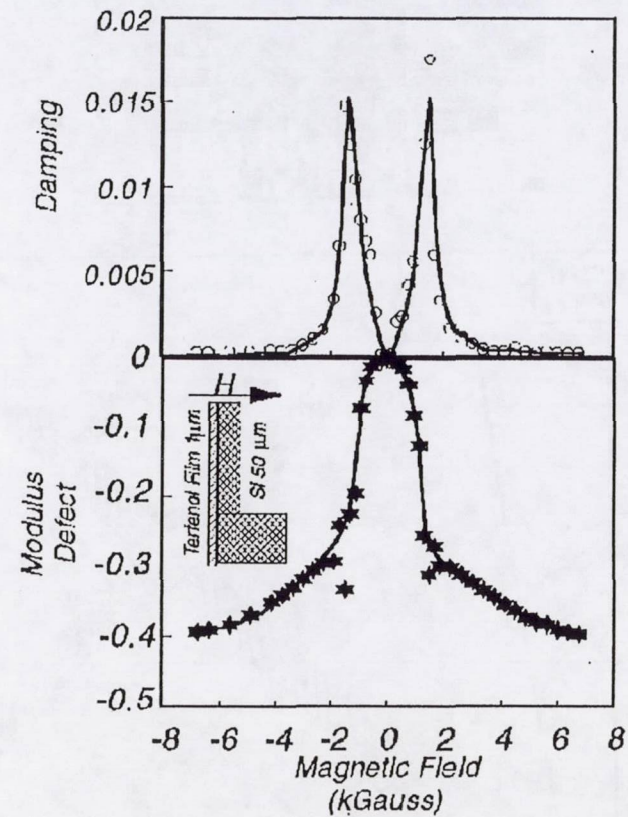


AFM MAGNETIC DOMAIN IMAGE



DOMAIN STRUCTURE

$$D_0^2 \propto h$$



GIANT DAMPING AND MODULUS DEFECT IN
TERFENOL FILM/SI SUBSTRATE COMPOSITE

$$\bar{Q}'_{(FILM)} = 1$$

$$\Delta E/E_{(FILM)} = -100\%$$

BIAXIAL LOADING EXPERIMENTS ON SHAPE MEMORY EFFECTS

CONSIDERATIONS:

INDEPENDENCE OF HYDROSTATIC STRESS
EXTREME SENSITIVITY TO SHEAR
ENERGETIC CONSIDERATIONS
HOMOGENEOUS DEFORMATIONS
NULL-LAGRANGIAN
ANISOTROPY OF MATERIAL

EXPERIMENTAL SET-UP:

UNIFORM STRESS EVEN WITH SHEAR DEFORMATIONS
TEMPERATURE CONTROL
INCREMENTAL LOADING AND CONTINUOUS LOAD PATH
BINARIZED VIDEO FRAME OF MICROSTRUCTURE
NUCLEATION AND ANNIHILATION OF TWIN

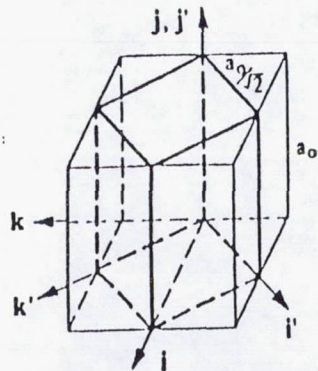
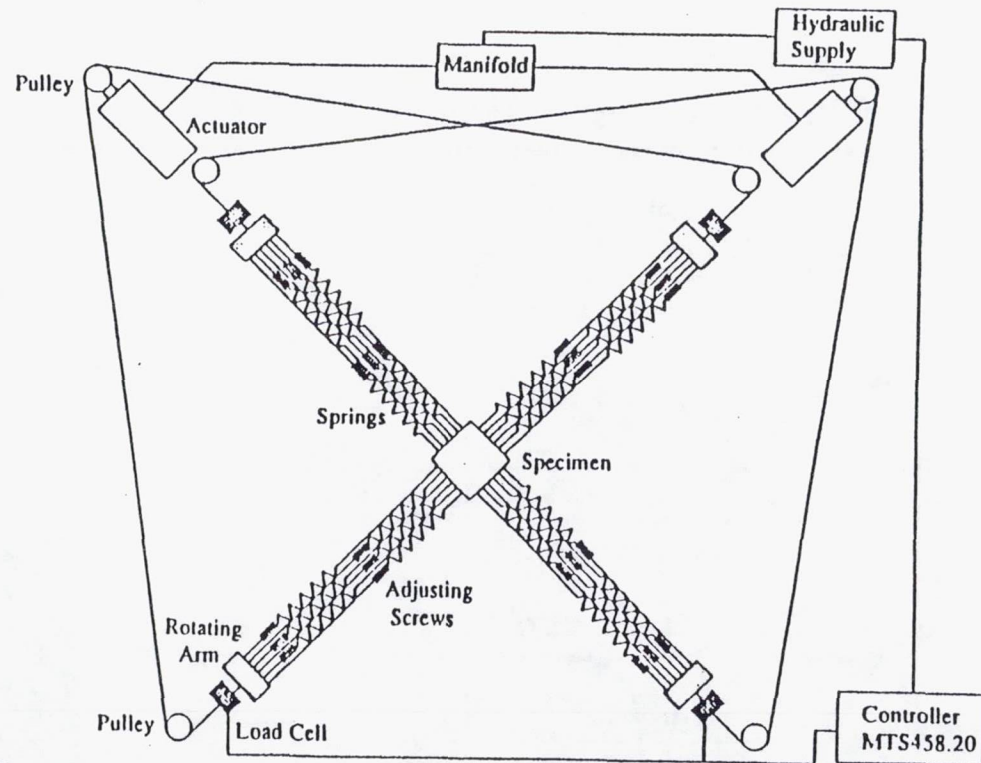


Figure 9a Lattice correspondence.
(i, j, k) are the cubic lattice vectors.

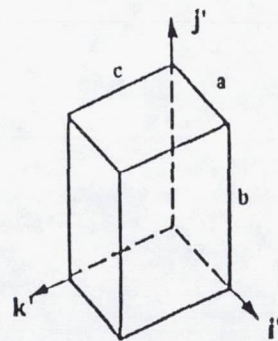


Figure 9b Orthorhombic unit cell.
(i', j', k') are the orthorhombic lattice vectors.

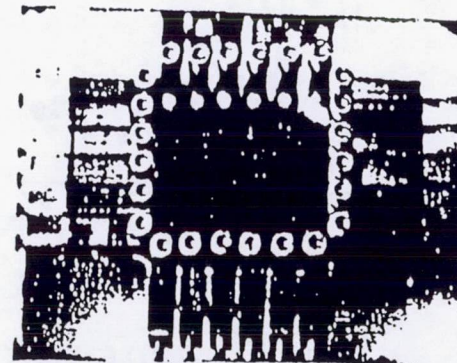
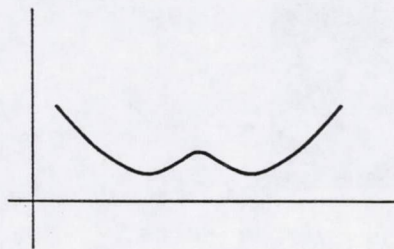
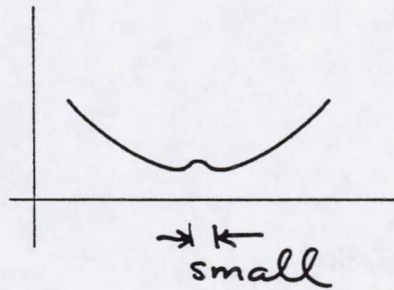
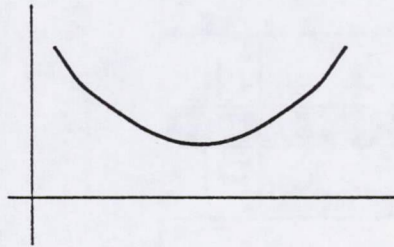
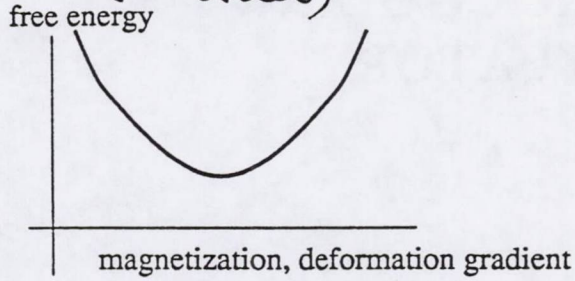


Photo 2 Grippled configuration.

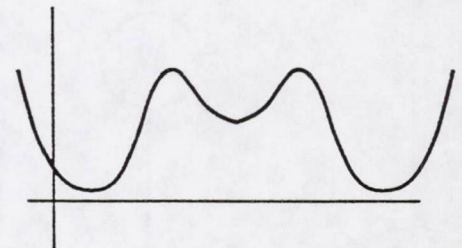
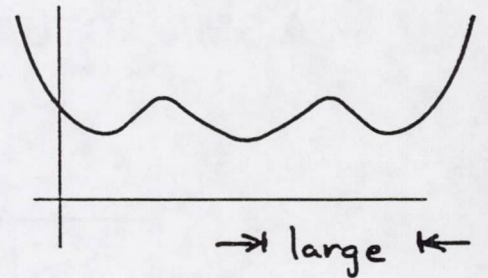
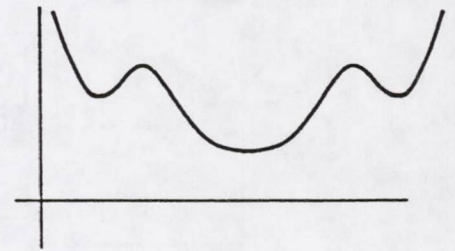
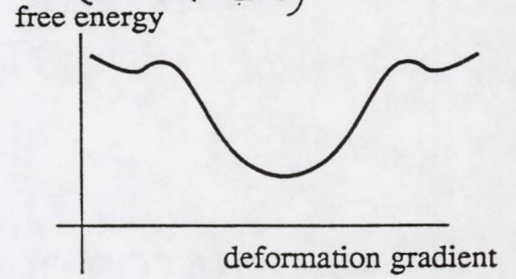
James / Minn.

Why do current magnetostrictive materials have such small strain?

current magnetostrictive
(2nd order)



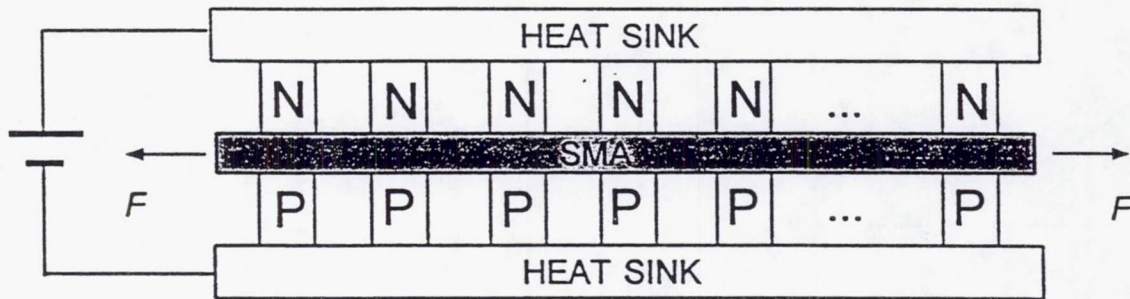
current shape memory
(1st order)



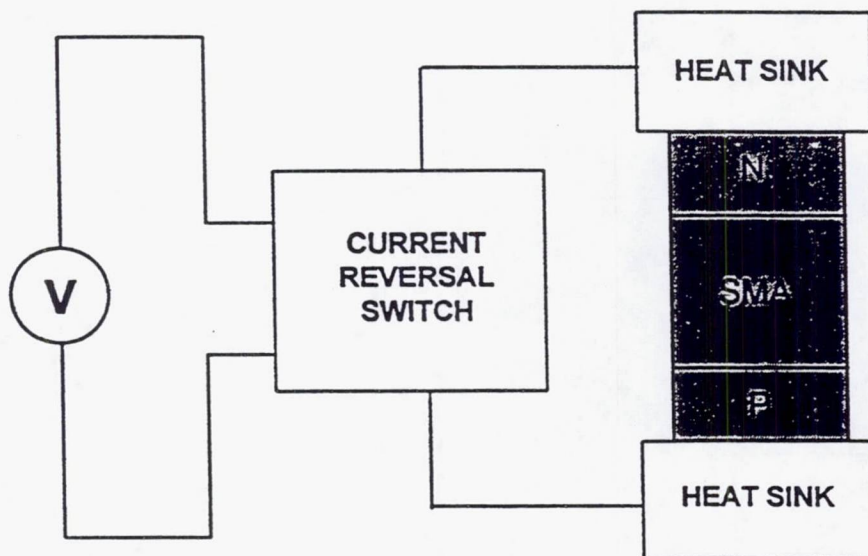
temperature

THERMOELECTRIC COOLING OF A SMA ACTUATOR

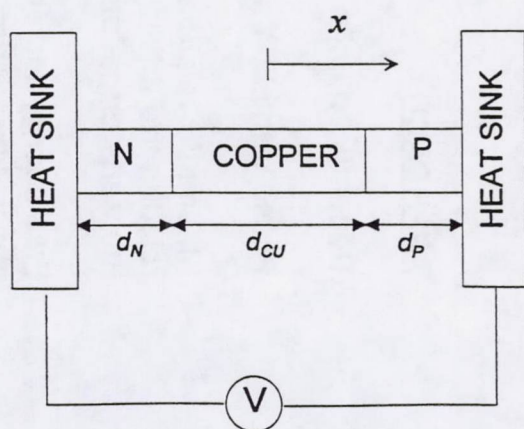
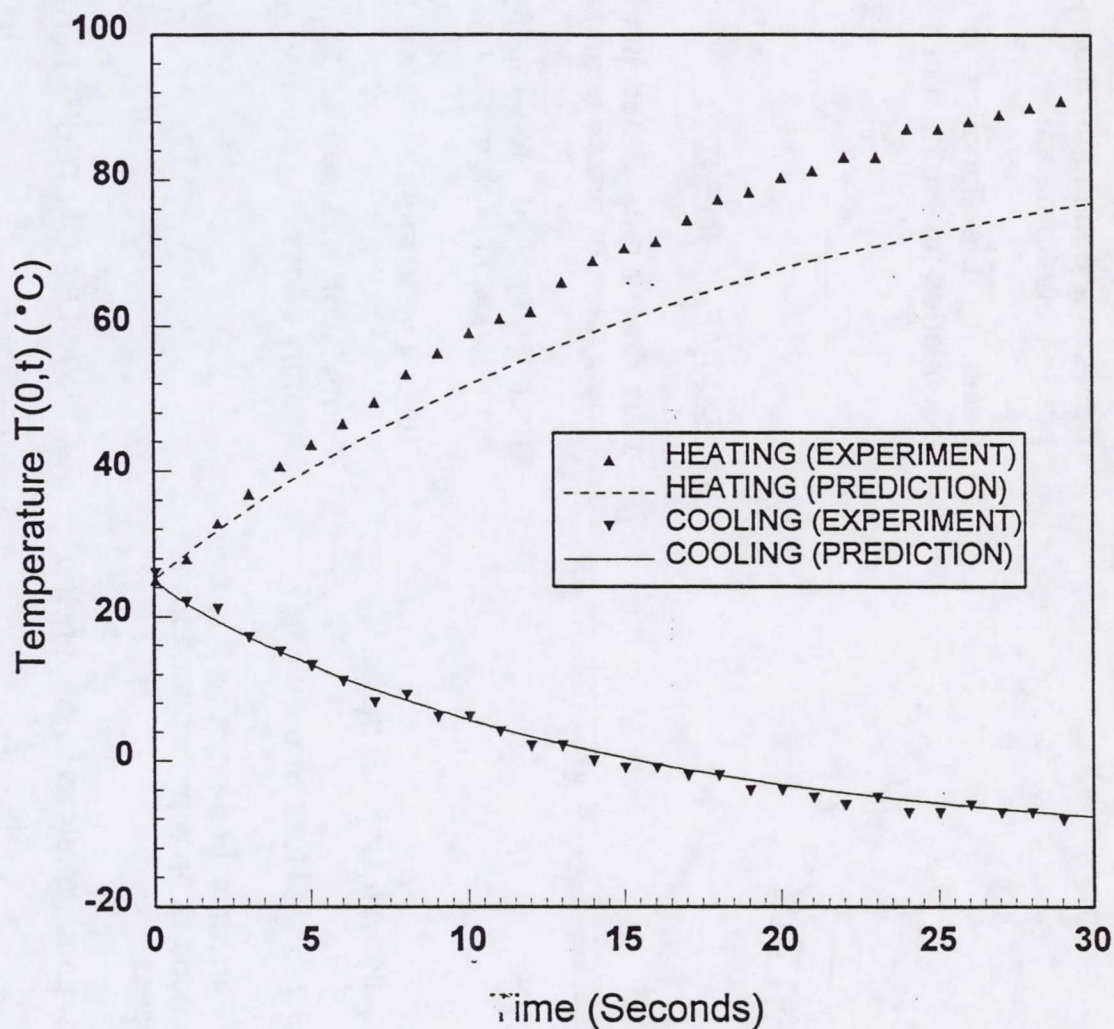
- ACTUATOR CONCEPT



- CURRENT EXPERIMENT ON THERMAL RESPONSE OF A SMA ACTUATOR CELL

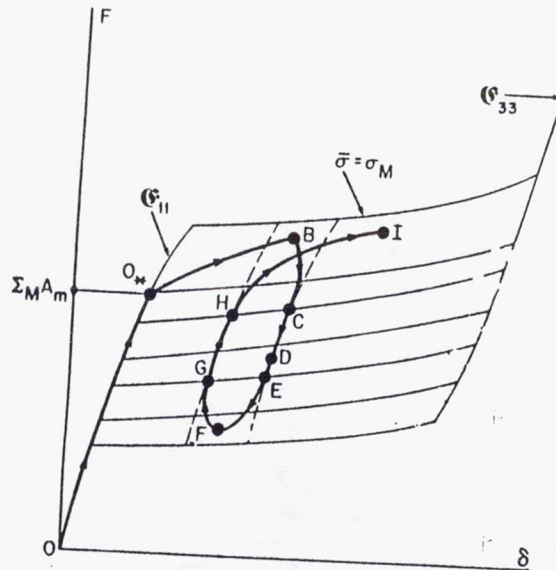


COMPARISON BETWEEN EXPERIMENTAL RESULTS AND MODELING PREDICTIONS



$$\begin{aligned}
 J &= 0.655 & A / \text{mm}^2 \\
 d_{CU} &= 6.22 & \text{mm} \\
 d_P &= d_N = 2.12 & \text{mm} \\
 \alpha_P &= -\alpha_N = 2.12 \times 10^{-4} & V / ^{\circ} K
 \end{aligned}$$

MECHANICS OF PHASE TRANSFORMATION IN THERMOELASTIC BEHAVIOR



OBJECTIVES :

Develop a continuum theory for a solid undergoing phase transformation.

Describe the kinetics of nucleation of phase boundaries for isothermal and dynamic conditions.

ACCOMPLISHMENTS :

New theory established the kinematic relations and propagation of phase boundaries.

Theory applied to rapidly propagating phase boundaries in high strain rates.

Results valid in three dimensions.

Formulation was applied to Intermetallics and shape memory alloys.

APPROACH

Generalized finite elasticity with singular fields.

Phase transition associated with loss of ellipticity.

Kinematic relations to eliminate non-uniqueness, by relating the driving tractions to entropy production of the transformation process.

Free energy and entropy considerations to identify the phase boundaries.

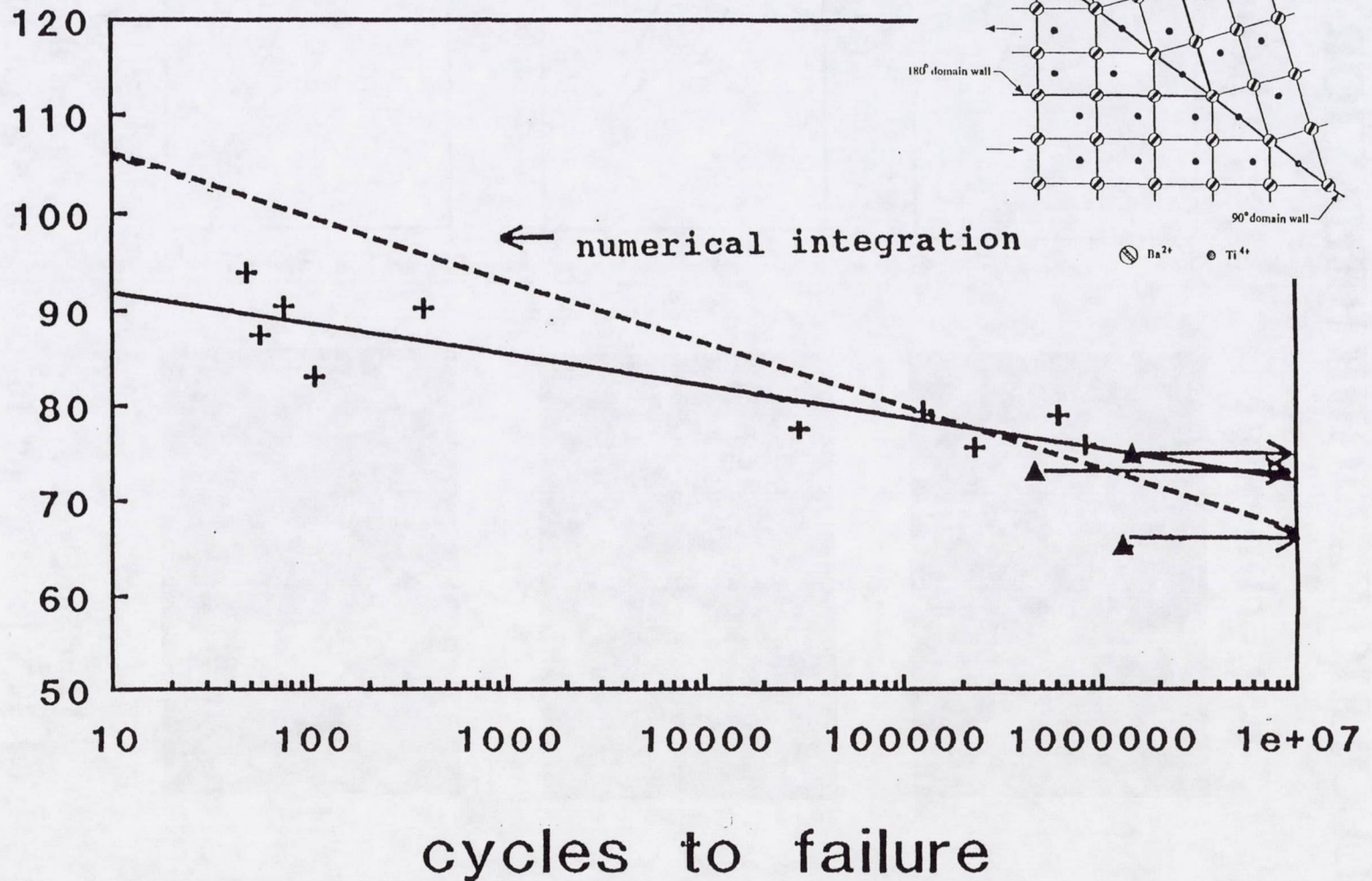
J. KNOWLES-CALTECH/ R. ABEYARATNE-MIT

S-N Curve PZT-8

300g Indentation

+ failure ▲ runout

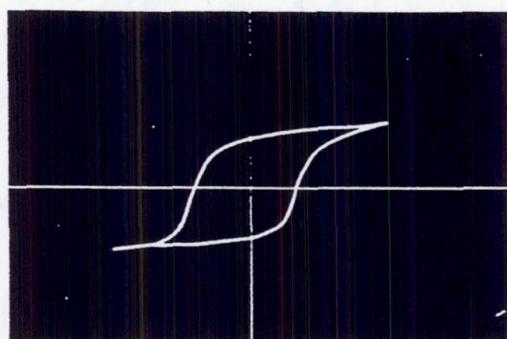
maximum stress (MPa)



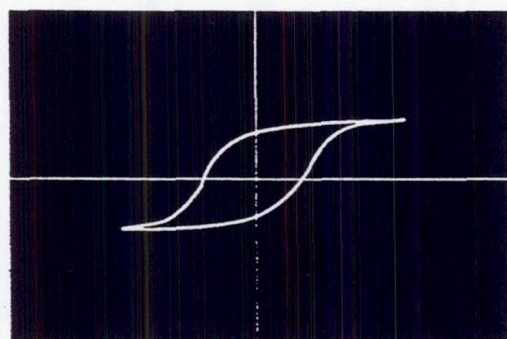
NIST / U. Nb.
white / time

ELECTRIC FATIGUE BEHAVIOR OF SOFT PZT

Experimental



(a)



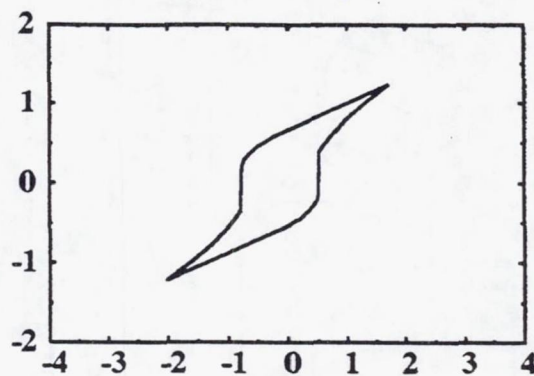
(b)



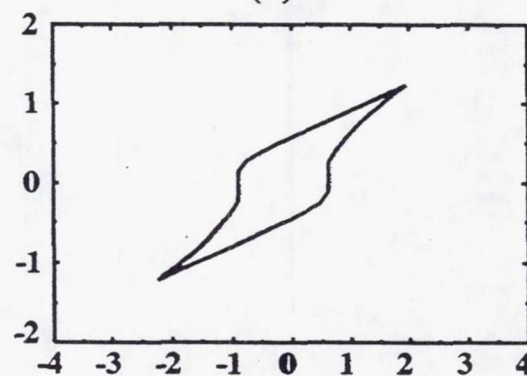
(c)

Loading Cycles:
(a) 10^3 (b) 10^7 (c) 10^9

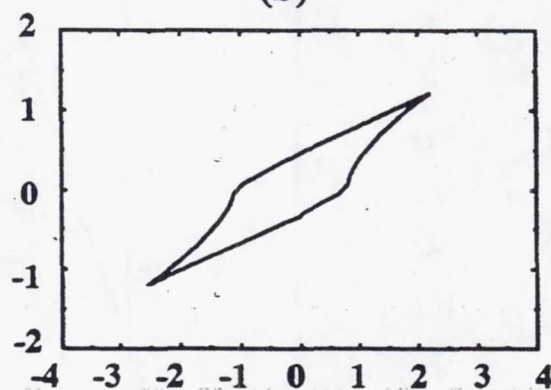
Theory



(a)



(b)

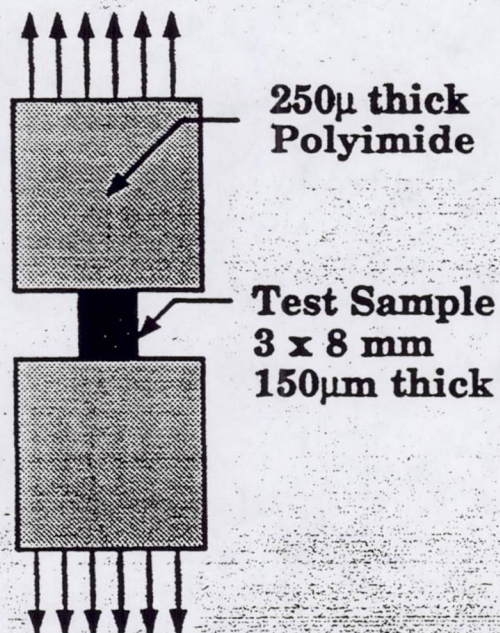


(c)

Pinned Domains are
(a) 5% (b) 10% (c) 20%

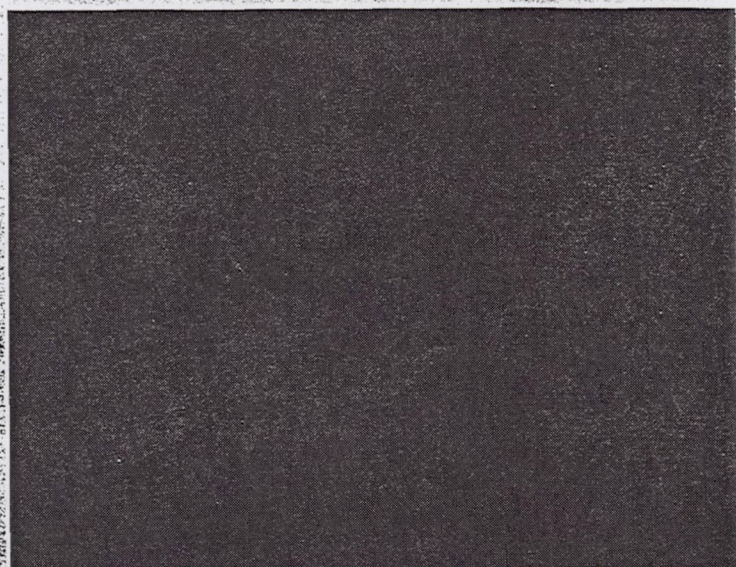
*The horizontal axis-normalized applied electric field intensity;
The vertical axis-normalized polarization intensity.

Birefringence shows Stress Field and Residual Switching (8/65/36 PLZT)

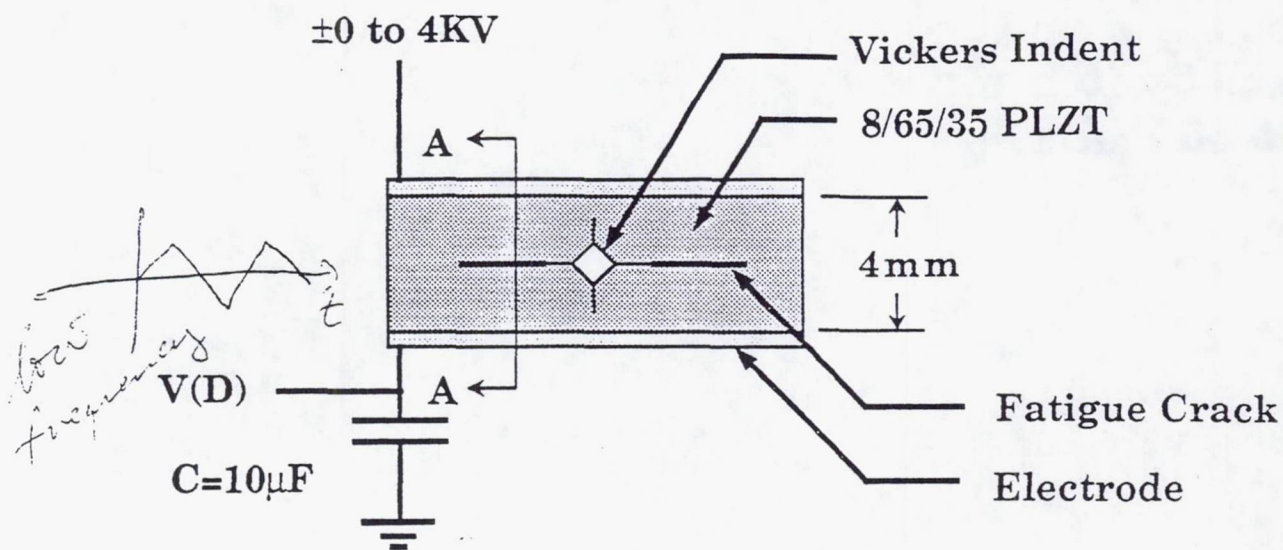


**Tensile Test
(Bond Polyimide to Grips
on Test Machine)**

**Sample viewed between
crossed polarizers with
quarter wave plates.**

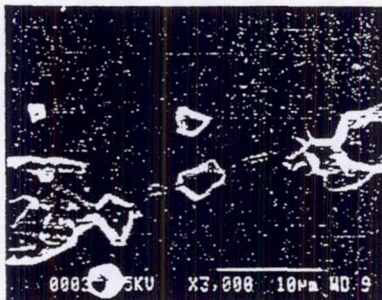


Electric Fatigue Cracks



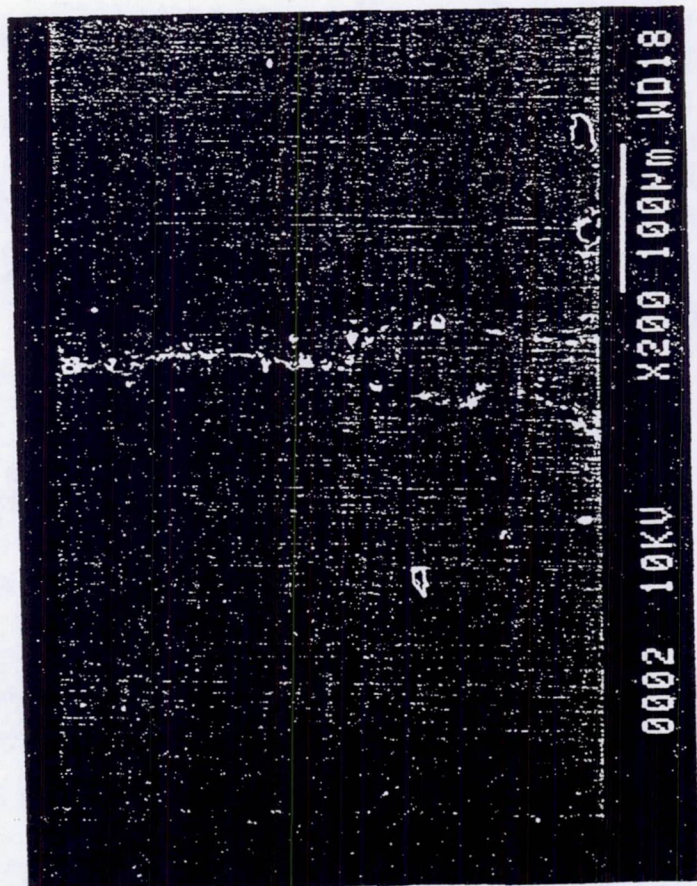
Front Surface

SEM

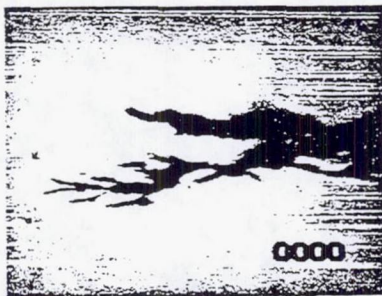


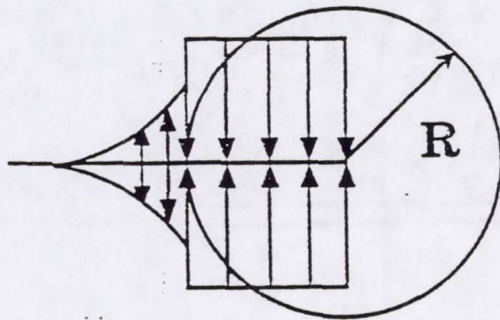
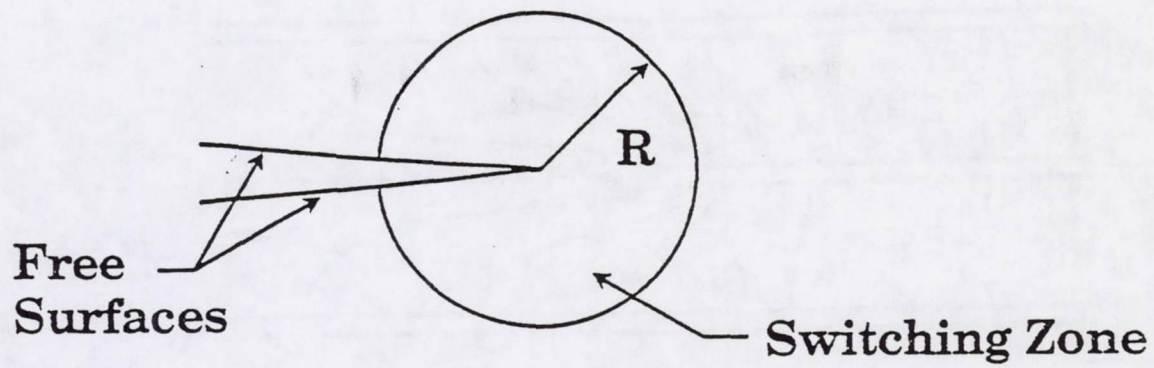
Section A-A

SEM

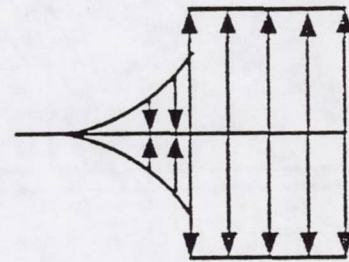


Optical





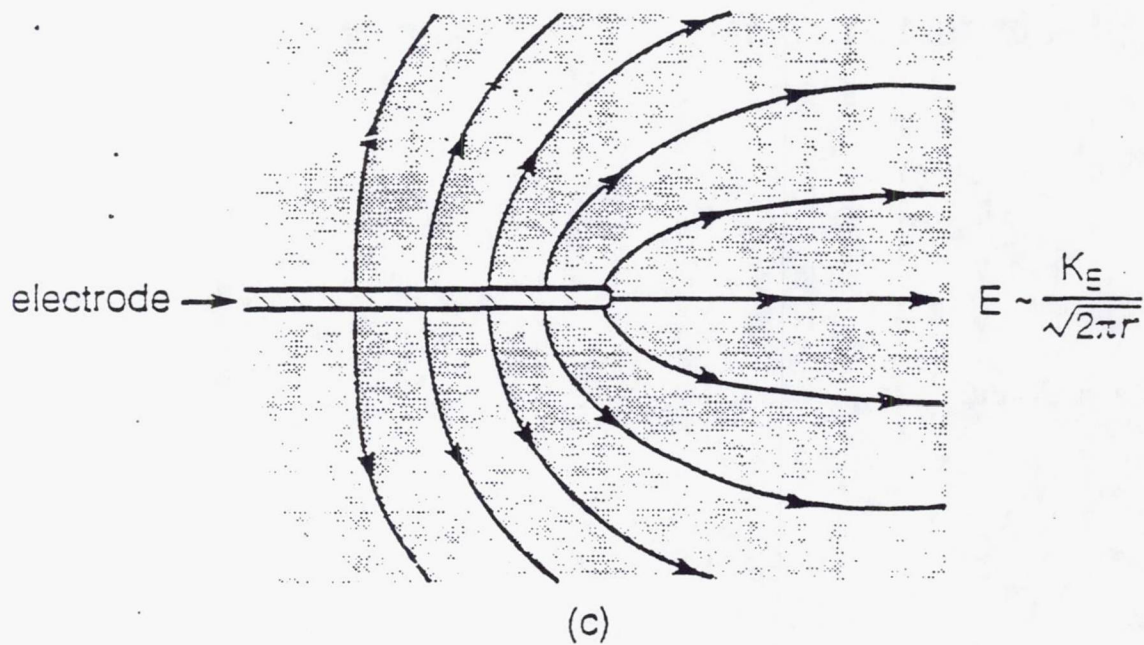
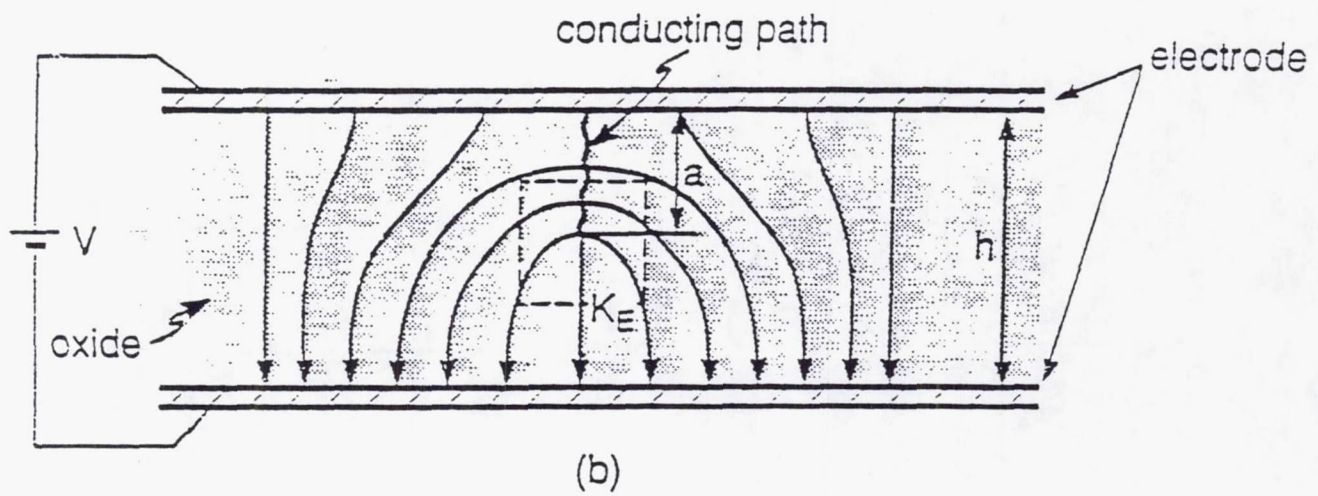
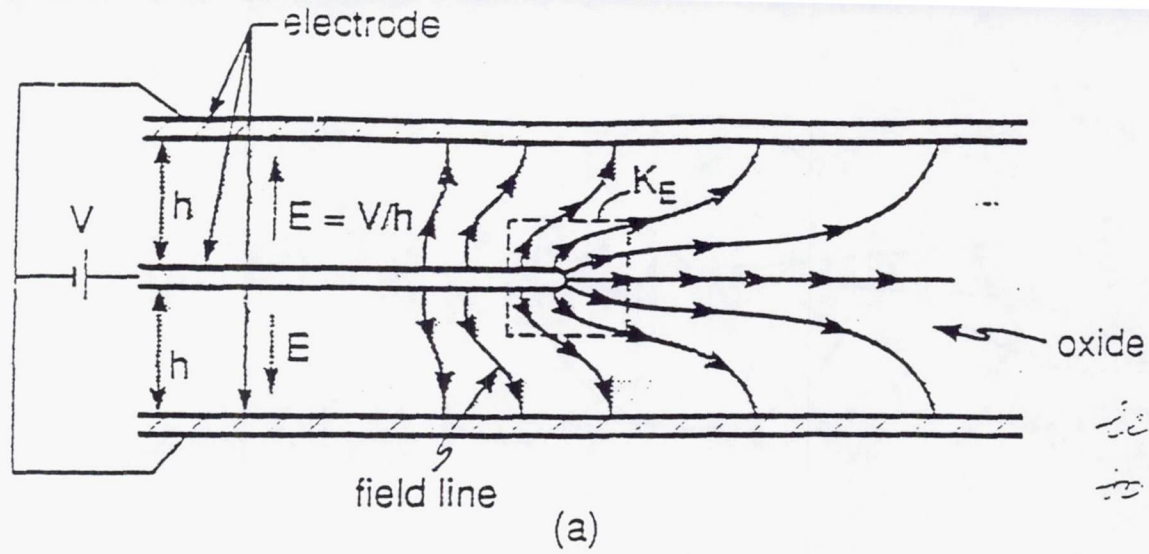
Electrostriction



Negating Traction

Figure 10. Lynch et al. / *Suo*

UCSB



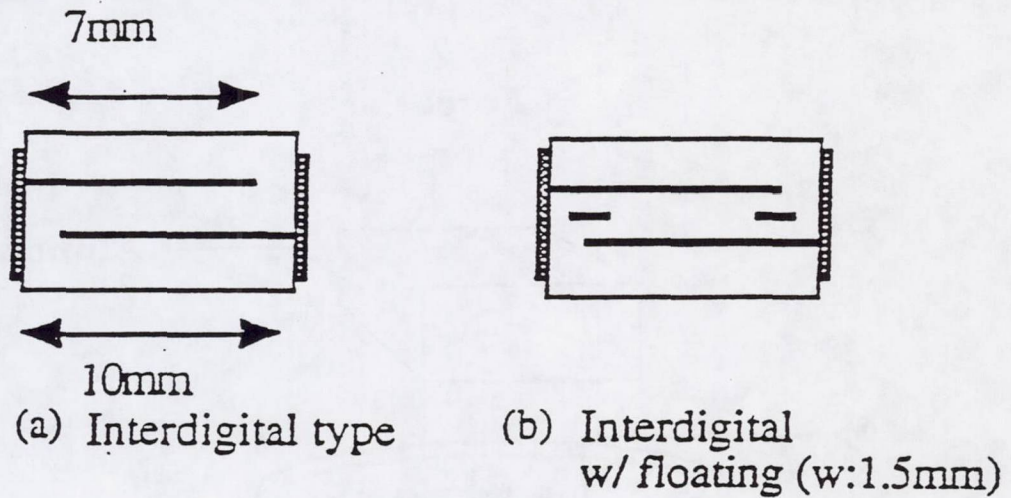


Figure 2 Structure of the samples. Layer thickness :200um.

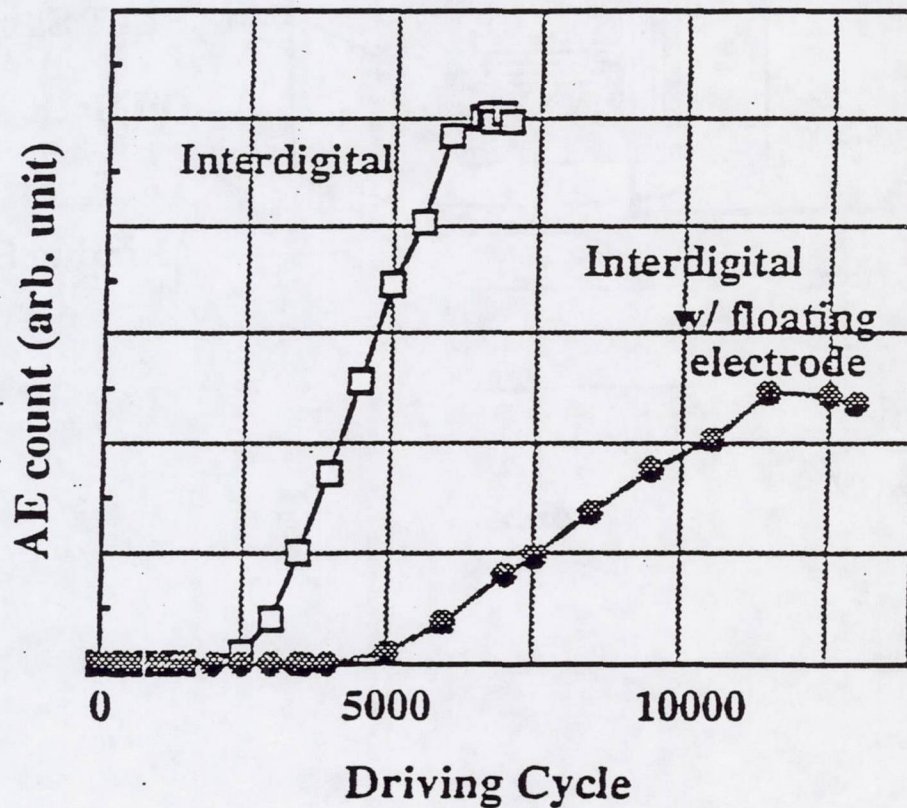
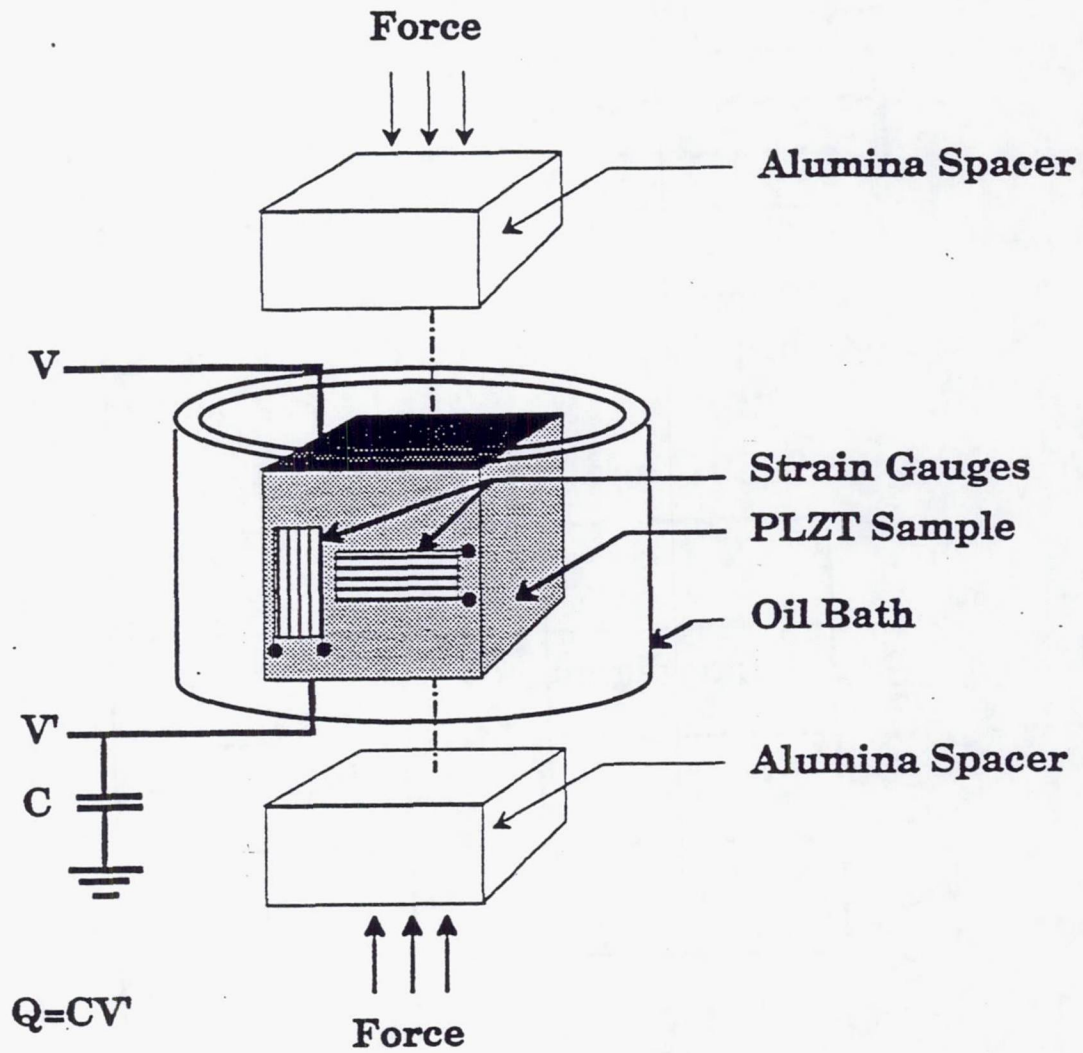
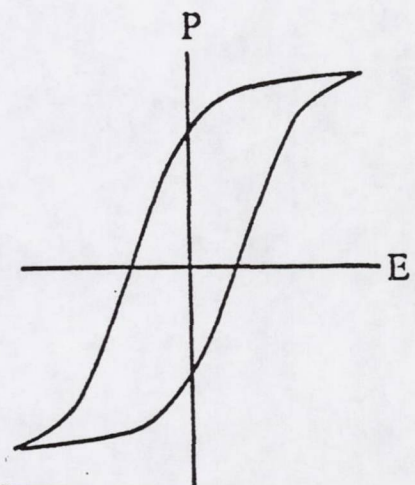
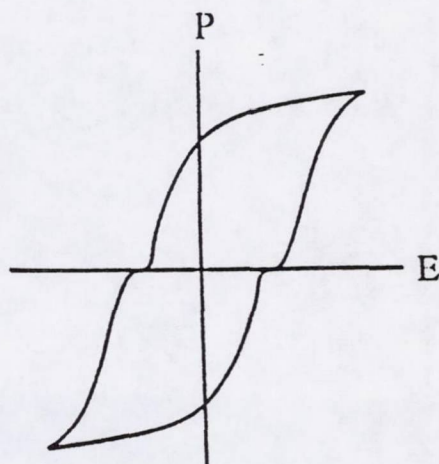
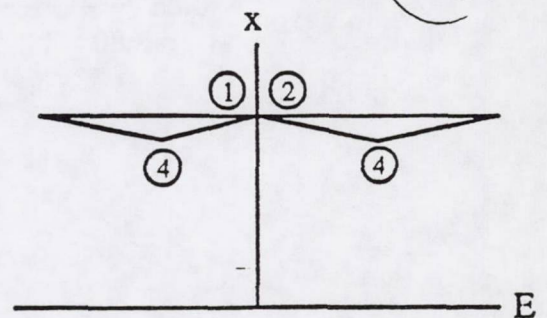
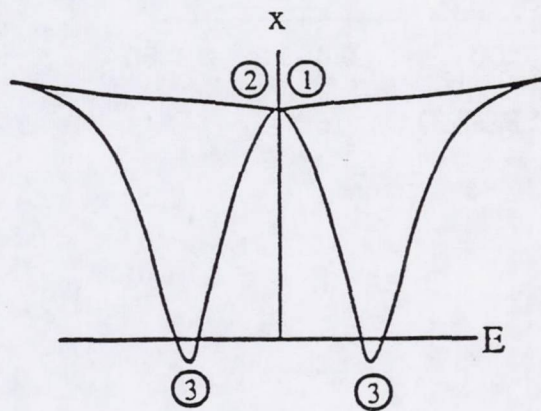
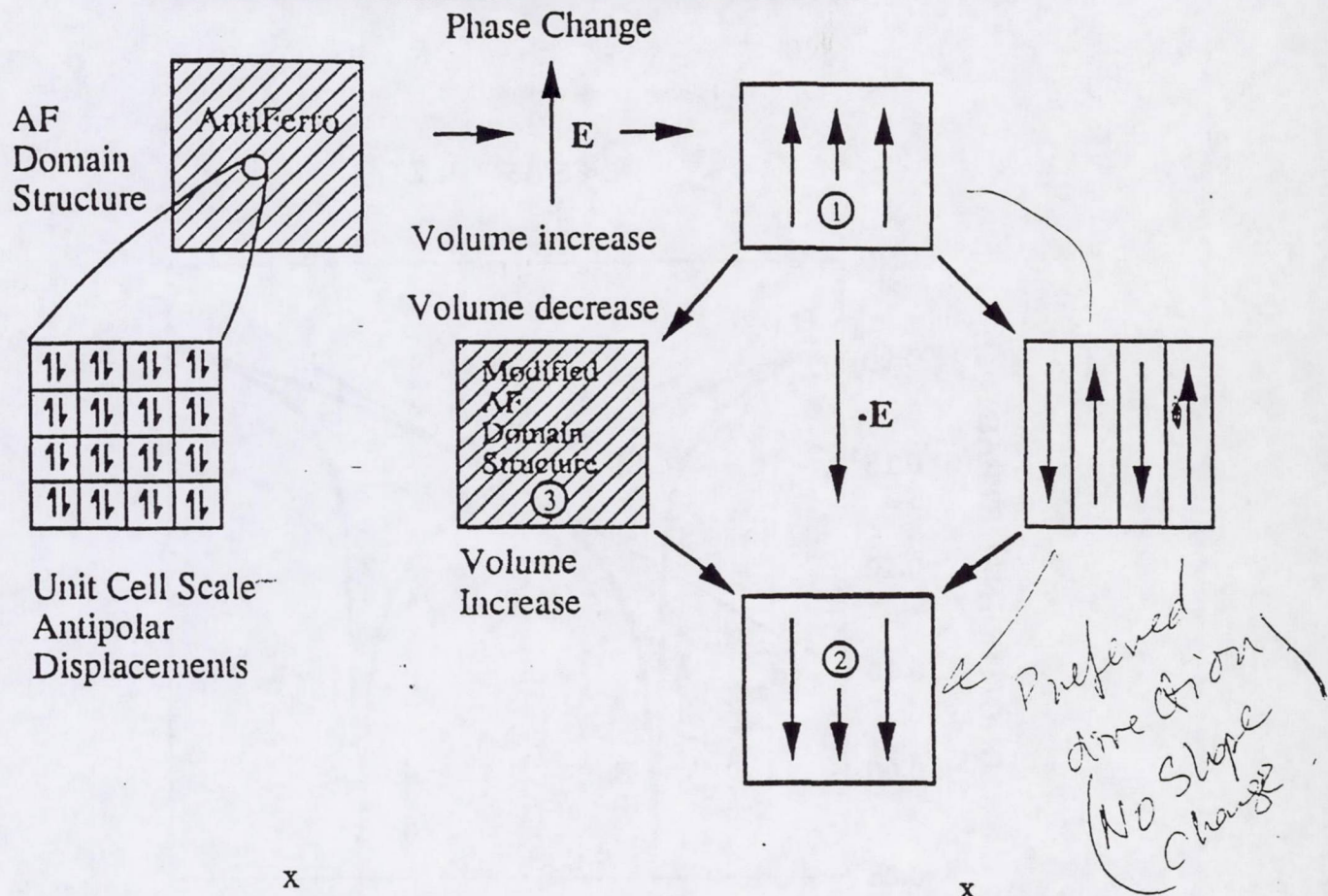


Figure 7 AE count in the interdigital and interdigital & floating electrode type actuators as a function of driving cycle.

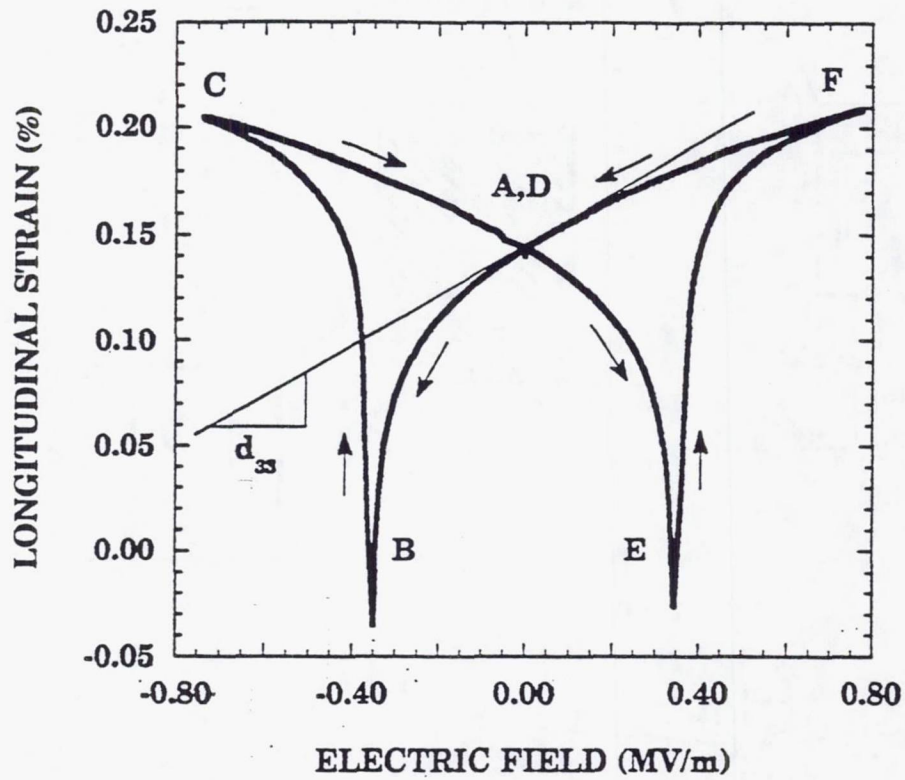
Experiments



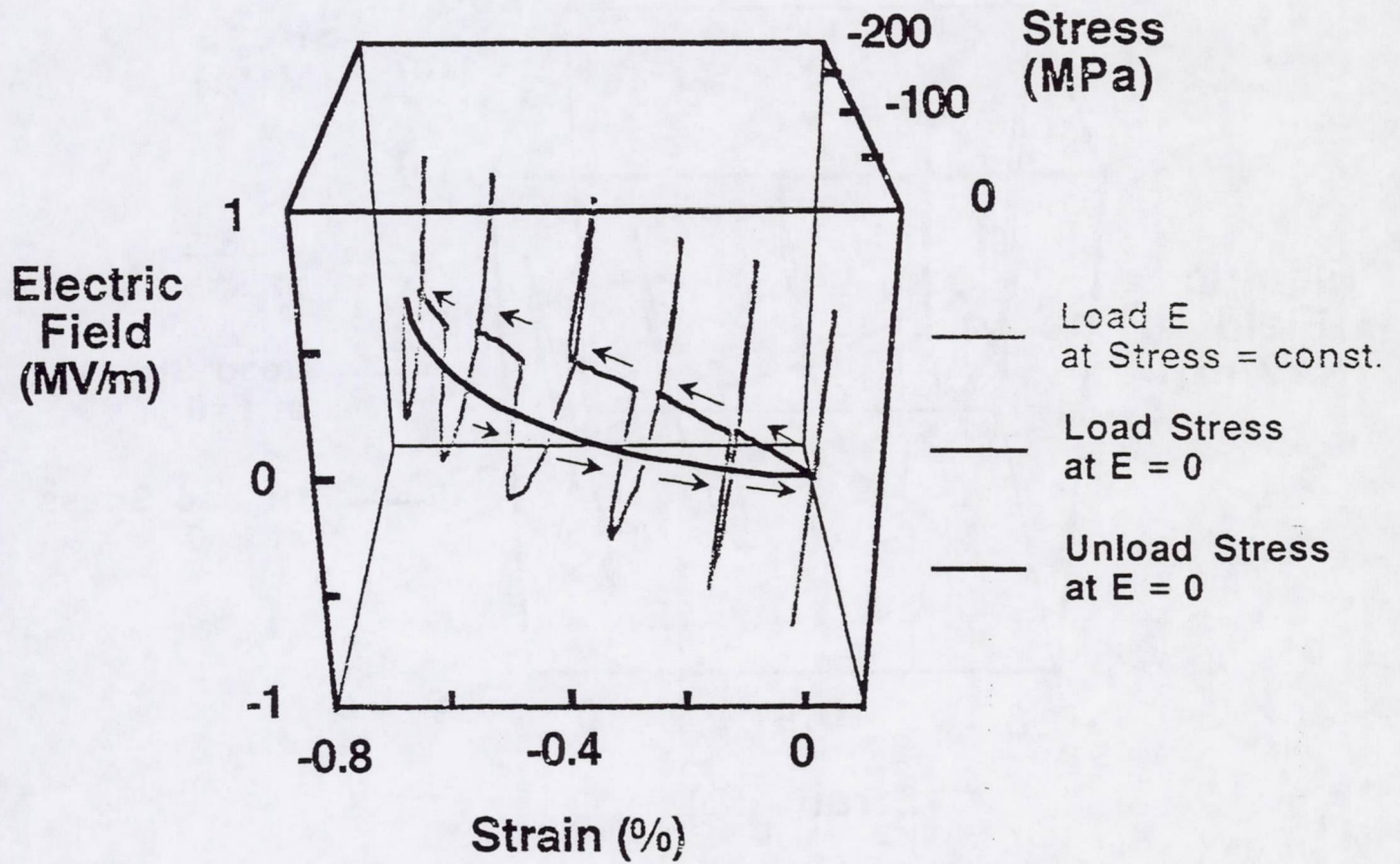
ANTIFERROELECTRIC TO FERROELECTRIC SWITCHING



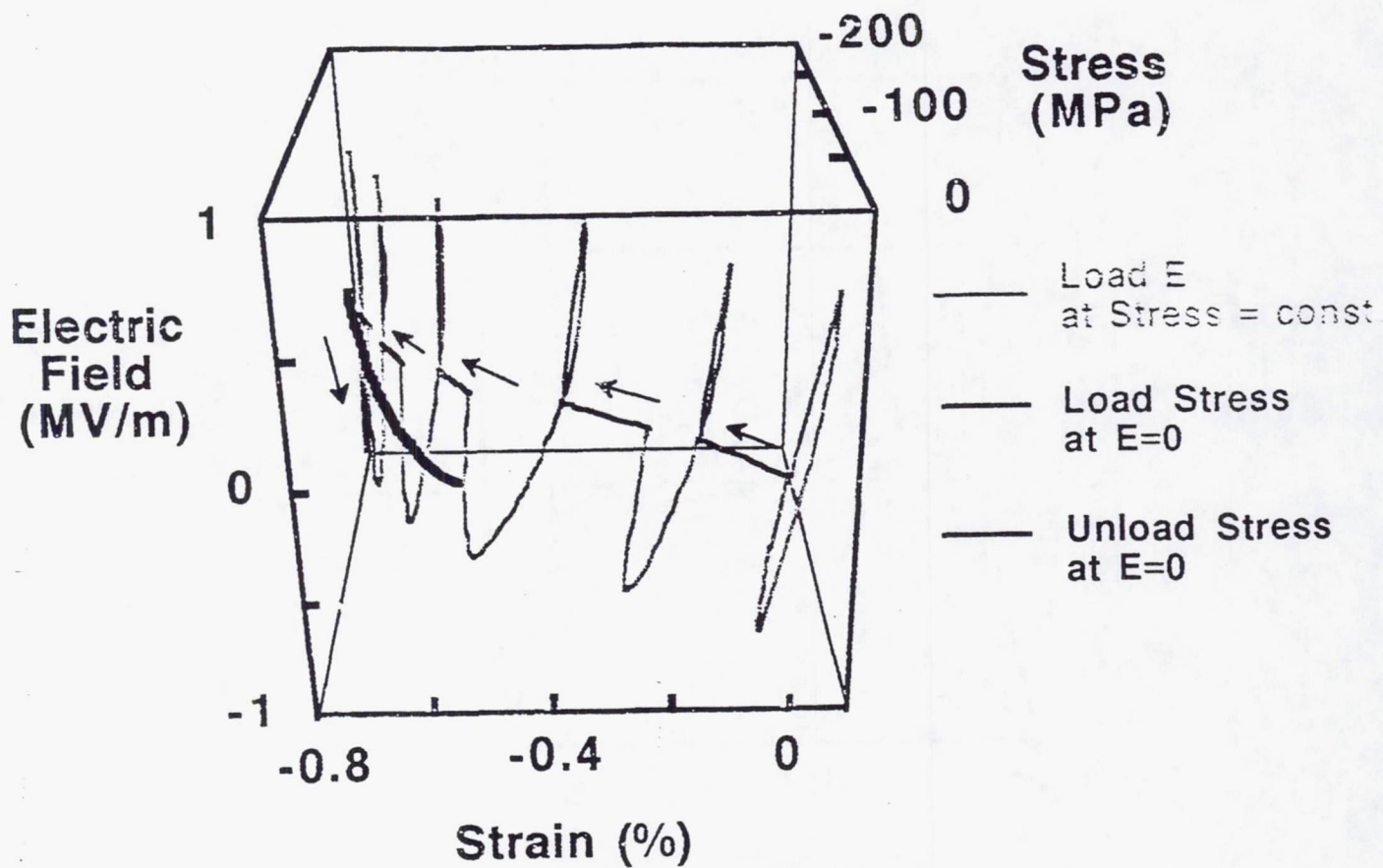
8/65/35 PLZT



C5804 Hard PZT

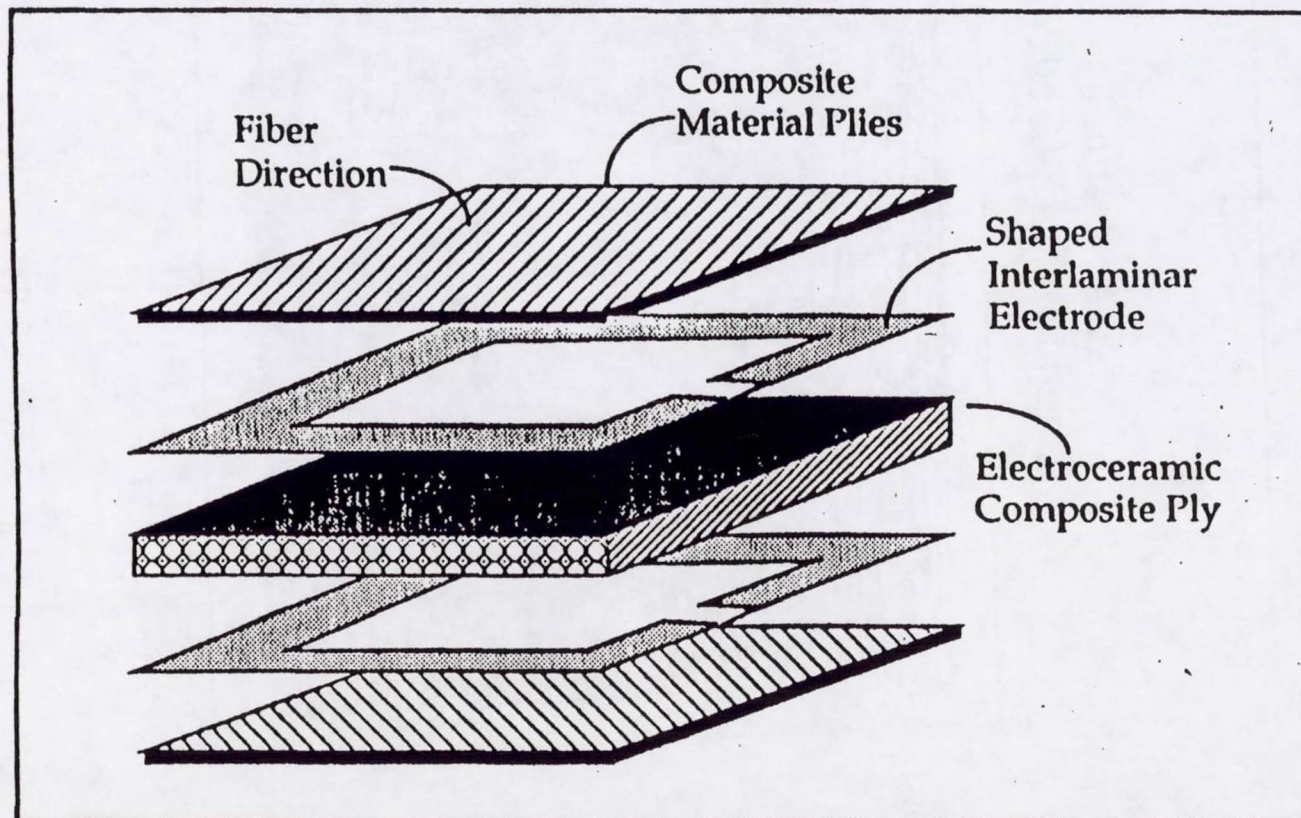


C5500 Soft PZT



Recent Work in Piezoelectric Fiber Composites for Structural Actuation

- Active Laminate formed with Electroceramic Composite Ply and shaped Interlaminar Electrodes

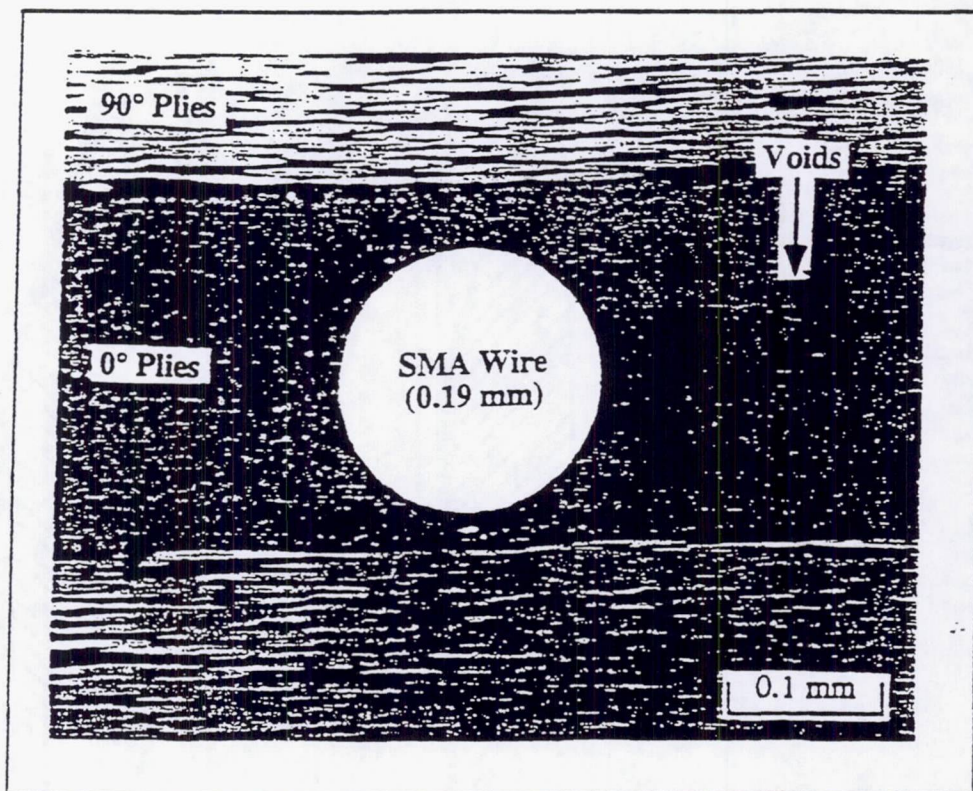


- Yields conformable, integrated actuators and sensors whose properties can be tailored for a given application

Nesbitt W. Hagood
MIT

Good Quality SMA Composite

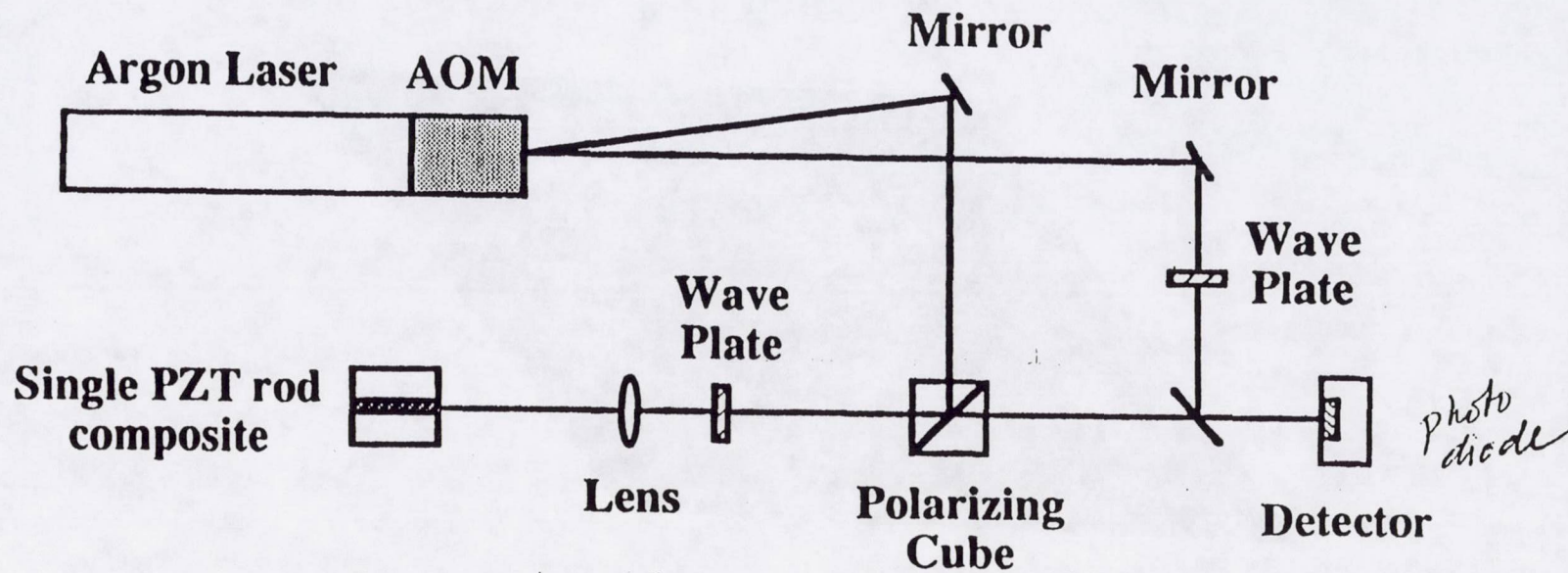
SMA: Nitinol
Composite: AS4/3501-6



200 X

- Staged cure cycle
- acetone wash
- Sectioned @ $x = 82$ mm

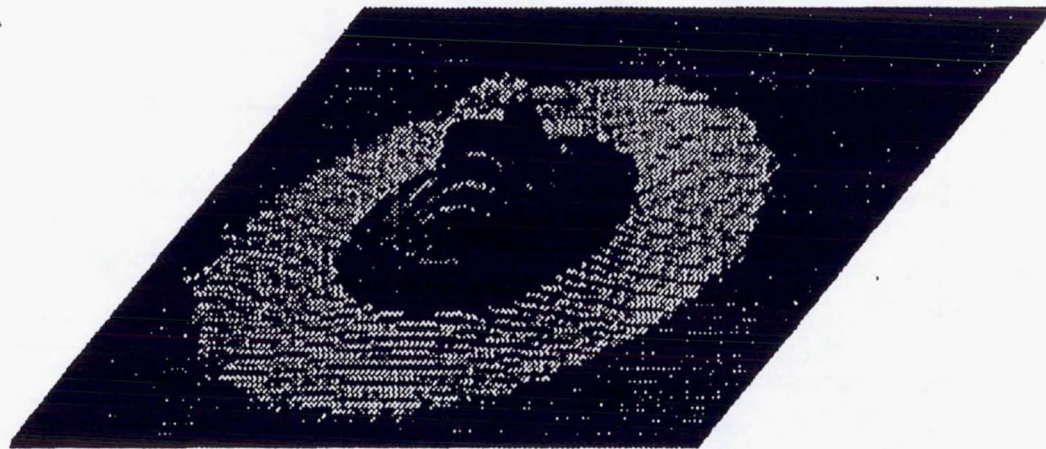
SCANNING INTERFEROMETER FOR TRANSIENT MEASUREMENTS



DYNAMIC DISPLACEMENT PROFILE

Maximum Displacement = $.006 \mu\text{m}$

2.0 kHz , 50 V rms



8 x 8 mm

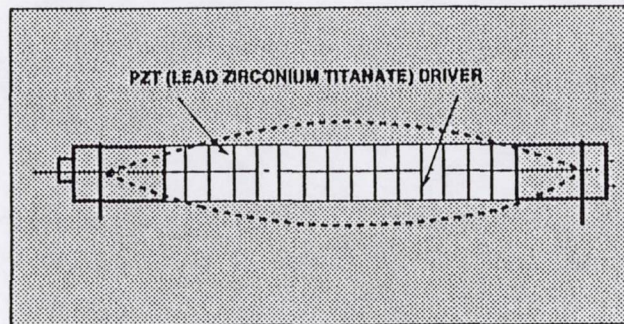


Figure 1. Bender bar projector.

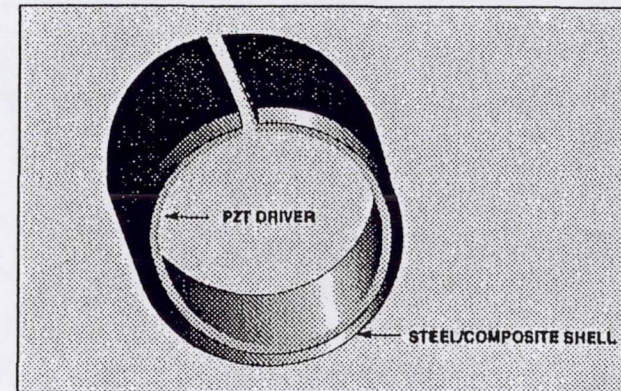


Figure 2. Split cylindrical transducer.

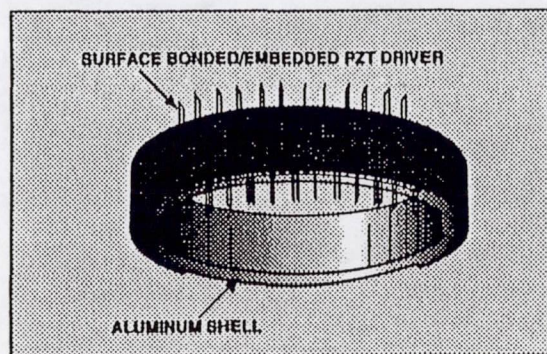


Figure 3. Wall-driven oval (WALDO) ring transducer.

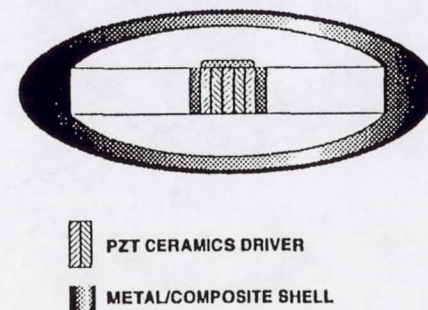
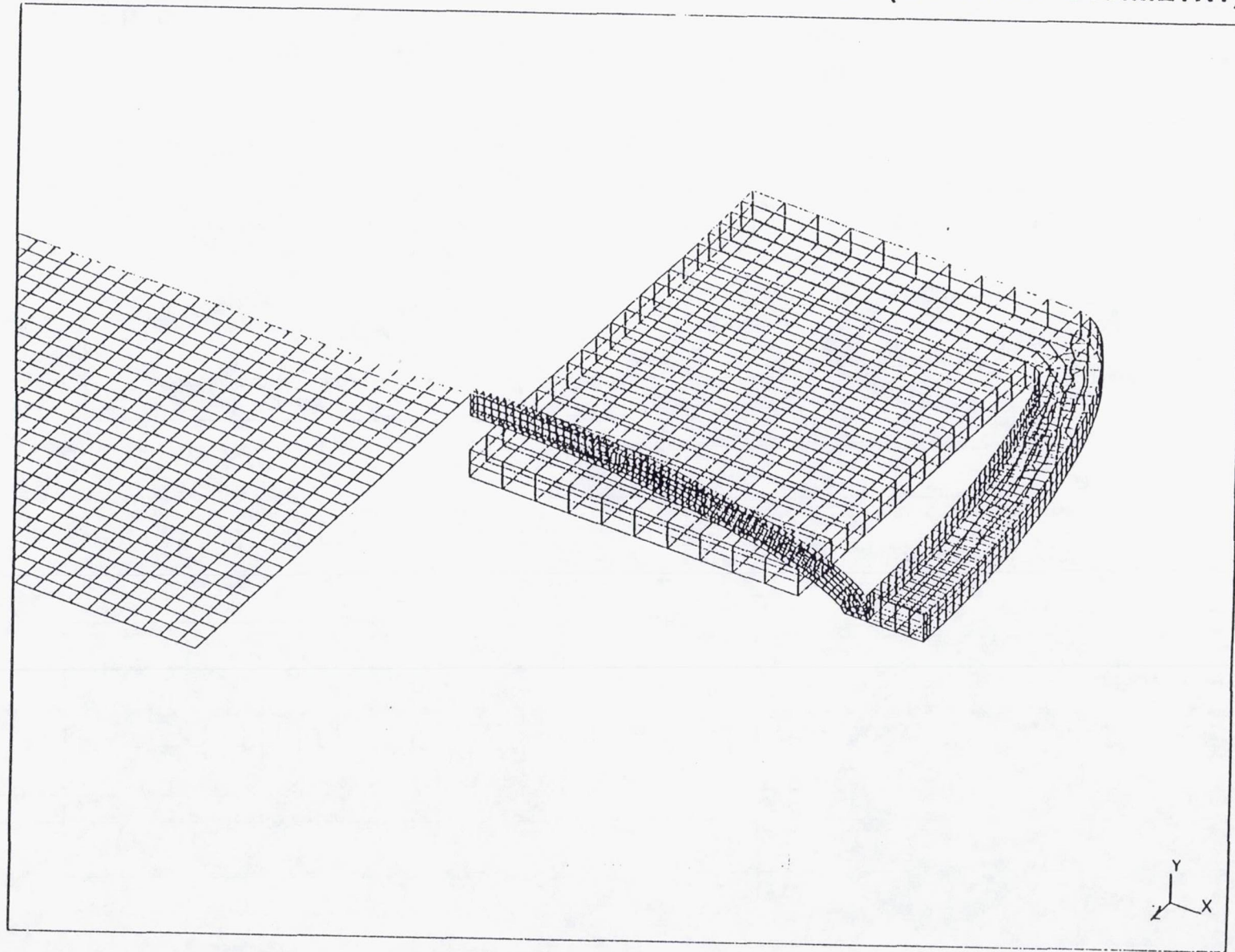


Figure 4. Class IV flextensional transducer.

TRANSDUCER DESIGN / OPTIMIZATION (contd)

FINITE ELEMENT MODEL - 6 BY 6 INCH UNIT CELL (QUARTER SYMMETRY)





MICROMECHANICS AND MECHANICS OF METALS (Cont'd.)

● Constitutive Modeling for Dynamic Failure

- Ductile Failure - A. Needleman (Brown)
- Kinetics of Stress Induced Phase Transformation - Pressure Shear Plate Impact - R. Clifton (Brown)
- Computational Methods in Dynamic Fracture - Element Free Galerkin - T. Belytschko (Northwestern)

● Mechanics of Thyristors, Semiconductors and Thin Films

- Mechanics of Materials for Power Electronics Control Devices - B. Freund (Brown)
- Micro and Nano Mechanics of Thin Film Structures - K.-S. Kim (Brown)
- Mechanics and Mechanical Properties of Heteroepitaxial Thin Film Structures - H. Gao and W. Nix (Stanford)
- Modeling of Deformation and Fracture in Electronic and Structural Thin Film Materials, P.M. Anderson (Ohio State U)

● Active Materials and Adaptive Structures

- Magnetostriction Effect-Prediction of Domain Structure - First Order Transformation and Enhanced Response - R. James (Minnesota)



MICROMECHANICS AND MECHANICS OF METALS (Cont'd.)

● Active Materials and Adaptive Structures (Cont'd.)

- Mechanics of Phase Transformation in Thermoelastic/Piezoelectric Behavior - J. Knowles (CAL TECH) and R. Abeyaratne (MIT)
- Constitutive Law Measurement and Modelling for Ferroelectric Ceramics - R. McMeeking (UCSB)
- Degradation Mechanisms for Ferroelectric Actuator Design - Z. Suo and A. Evans (UCSB)
- Concurrent Engineering Adaptive Quiet Structures - G. Koopmann (Penn St.)
- Mechanically Adaptive Microcomposites - A. Roytburd and M. Wuttig (U. MD) Super Composite Projectors - NRaD, Po-yun Tang
- Optimization of Internal Interfaces of Composite with Embedded Actuator by Cure Cycle Optimization - Scott White (U Illinois) (YIP93)
- Investigation of Microscopic Mechanisms of Failure of Electronic Smart materials/Systems - Q. Jiang (U Nebraska)
- Design of High Frequency SMA Actuators - D.C. Lagoudas and V. Kinra (Texas A&M U)
- Cyclic Damage in PZT - G. White (NIST)

FUTURE APPLICATIONS OF ACTIVE MATERIALS / ADAPTIVE STRUCTURES

- STRUCTURAL ACOUSTIC CONTROL
- NOISE AND VIBRATION CONTROL
- SENSORS FOR CONDITION BASED MAINTENANCE
- SHIPBOARD INTELLIGENT MACHINERY CONTROL
- REAL-TIME TARGETING
- DAMAGE CONTROL
- FLOW CONTROL
- TRANSDUCERS
- BATTLE DAMAGE - IDENTIFICATION, ASSESSMENT AND CONTROL
- FLEXIBLE RESPONSE

Page intentionally left blank



The ARPA Smart Materials and Structures Program

presented at
NASA Langley Research Center
4 May 1995

C. R. Crowe
Defense Sciences Office
Advanced Research Projects Agency



SMART MATERIALS AND STRUCTURES PROGRAM



- **Objectives: Develop material and structures which have the ability to sense and respond to their environment under active control**
 - **Noise and vibration control**
 - **Aerodynamic and hydrodynamic flow control**
 - **Structural shape control**

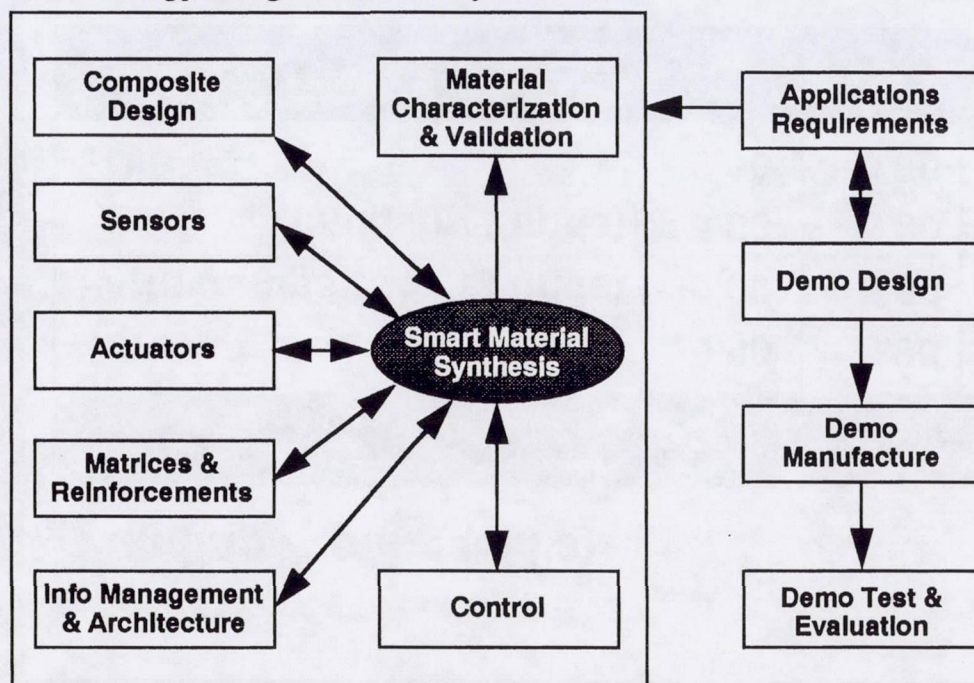


THE ARPA SMART MATERIALS AND STRUCTURES PROGRAM



Approach

Technology Integration and Optimization



• Research focus:

- New materials
- New components
 - Sensors
 - Actuators
 - Devices
- Design tools
- Integration technology
- Manufacturing technology
 - Embedment technology
 - IPM technology
- Product definition



THE ARPA SMART MATERIALS AND STRUCTURES PROGRAM *Funding*



Funding Profile: (\$M's)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Core	0.50	5.90	8.40	8.00	7.00	4.00
Partnerships (Gov't Funds)	5.00	5.80	0.65	0.60	0.40	
(Industry Funds)	5.00	5.80	0.60	0.60	0.40	
SDIR's	0.50	0.60	0.60	0.65	0.40	

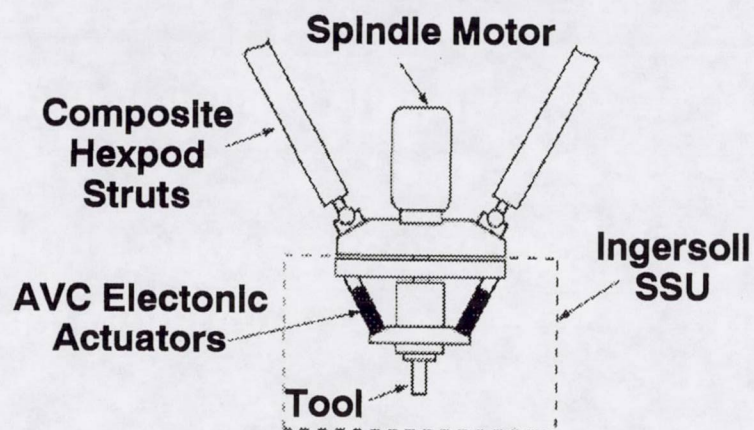
Six Year Program Effort: \$57.4M



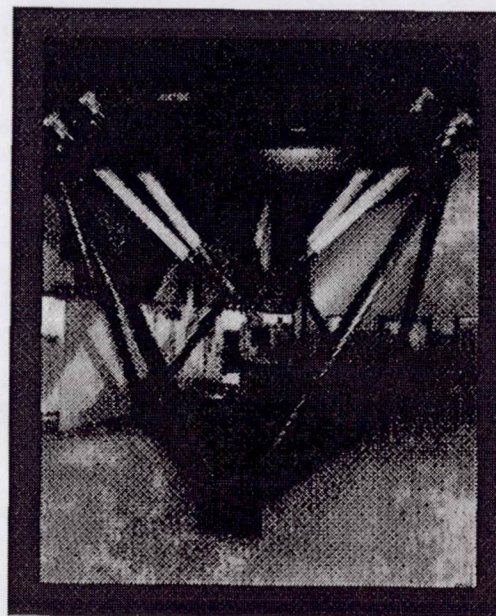
ADVANCED RECONFIGURABLE MACHINE FOR FLEXIBLE FABRICATION



ACTIVELY STABILIZED MACHINING PLATFORM



- Structural Dynamics Modeling
- Workpiece-Tool Interaction
- Active Vibration Control
- Machine Trials



ADVANCED RECONFIGURABLE MACHINE for FLEXIBLE FABRICATION (ARMF³)

MARTIN MARIETTA

Team Members

Team Member

Role

Martin Marietta Laboratories

**Prime Contractor, Actuator, Sensor
Subsystem**

Ingersoll Milling Machine Co.

**Machine Tool Design, Fabrication
and Testing**

Martin Marietta Astro Space

Composites

Intelligent Automation, Inc.

Modeling and Controls

Jet Propulsion Laboratory

Structural Models, Spacecraft Pointing

Sandia National Laboratories

Machine Models and Characterization

NIST

Metrology

Funding

Period of Performance

Point of Contact

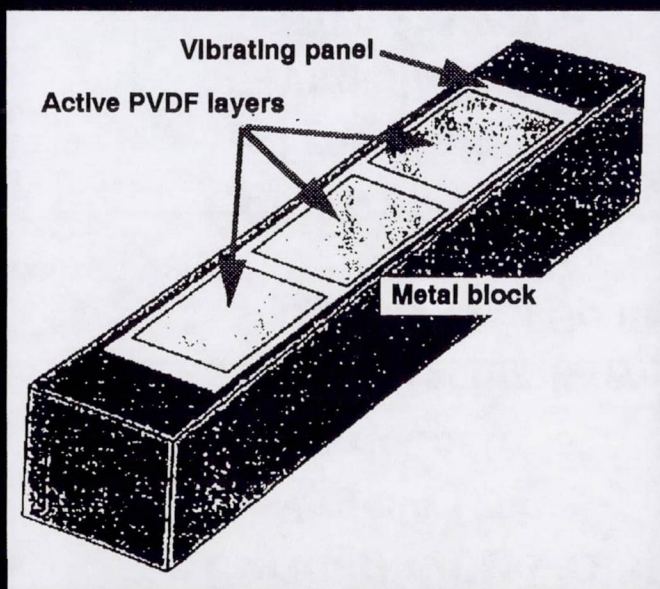
\$4.2M

November 1, 1994 - November 1, 1995

**Dr. Arthur Cooke
(410) 204-2354**



ACTIVE SURFACE COATING FOR ACOUSTIC APPLICATIONS



- **Develop Elementary Active Coating Concepts (Actuator, Sensors, Control, Electronics)**
- **Fabricate Active Coatings**
- **Test System As an Aircraft Cockpit Noise Reduction Applique**



ACTIVE SURFACE COATING FOR ACOUSTIC APPLICATIONS



- **Participating Organizations**

- Virginia Tech
- Barry Controls
- Hood Technology Corporation
- University of Southampton

- **Point of Contact**

- Prof> Chris Fuller
- Virginia Tech
- (703) 231-7273

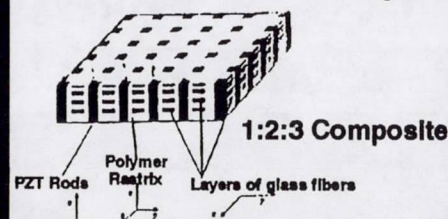
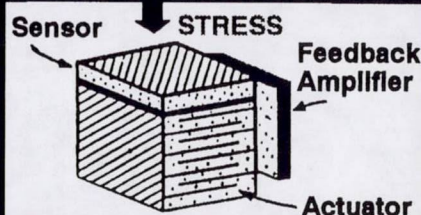
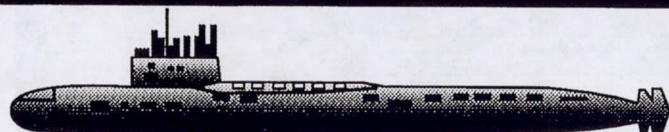
- **Funding Profile (\$K)**

<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
160	320	320



SMART MATERIALS AND STRUCTURES

Active Acoustic Coatings for Signature Suppression

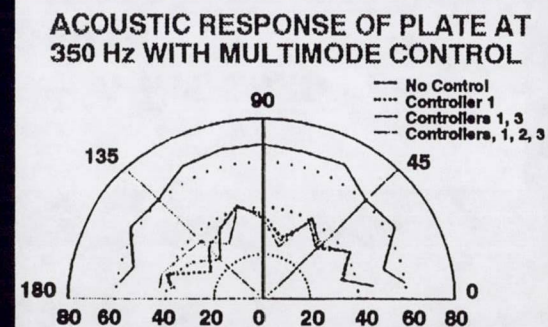
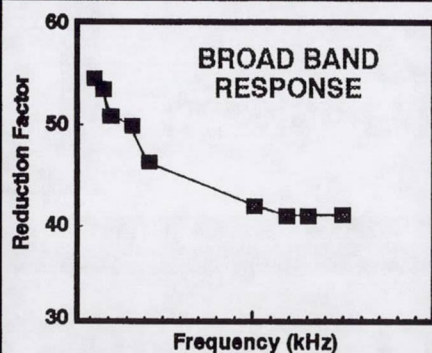


REQUIREMENTS

- Small Movements ($\mu\text{m}'\text{s}$)
- Response Times
 - Dynamic (kHz, localized control)
 - Static (long-wavelength, distributed control)

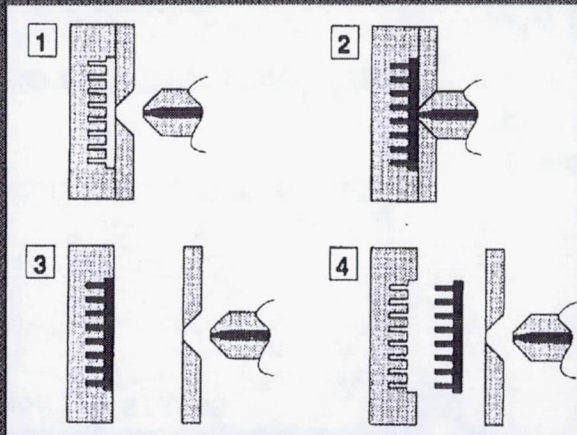
PAYOFF – ACTIVE ACOUSTIC STEALTH

- Up to 60 dB Reduction in Radiated Noise
- 100x Increase in Settling Times

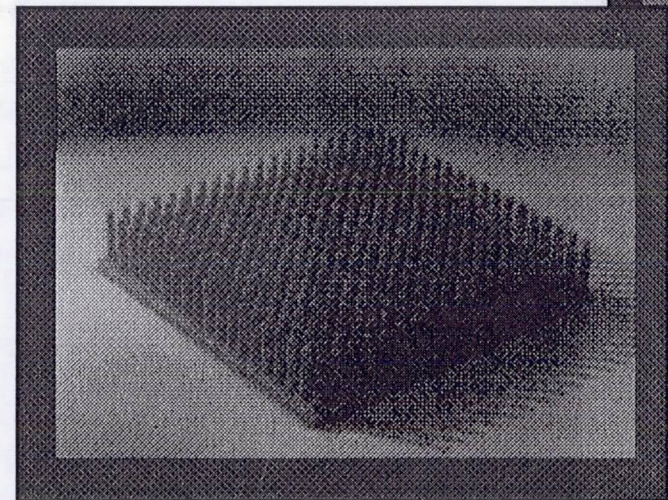
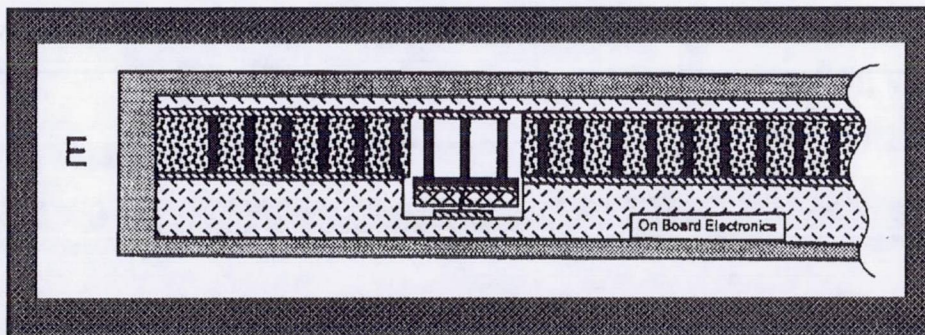




PIEZOELECTRIC COMPOSITES FOR ACTIVE SURFACE CONTROL



- Develop Fabrication Process For 1 - 3 Composites
- Design and Fabricate 1 - 3 Smart Composite Panels
- Test Panels





PIEZOELECTRIC COMPOSITES FOR ACTIVE SURFACE CONTROL



- **Participating Organizations**

- Material Systems, Inc.
- Naval Research Laboratory, Washington
- Naval Research Laboratory, Orlando

- **Point of Contact**

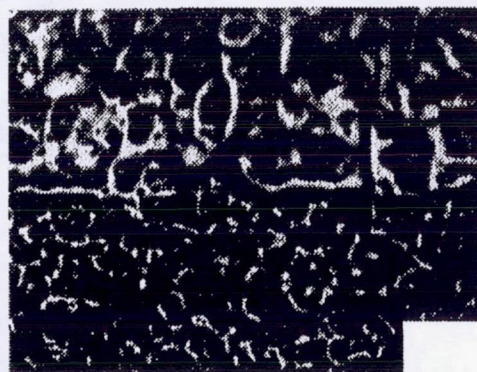
- Dr. Richard Gentilman
- Material Systems, Inc.
- (508) 486-0404

- **Funding Profile (\$K)**

<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
501	903	603



ELECTRO-ACTIVE ELASTOMERIC STRUCTURES FOR HYDROACOUSTIC APPLICATIONS



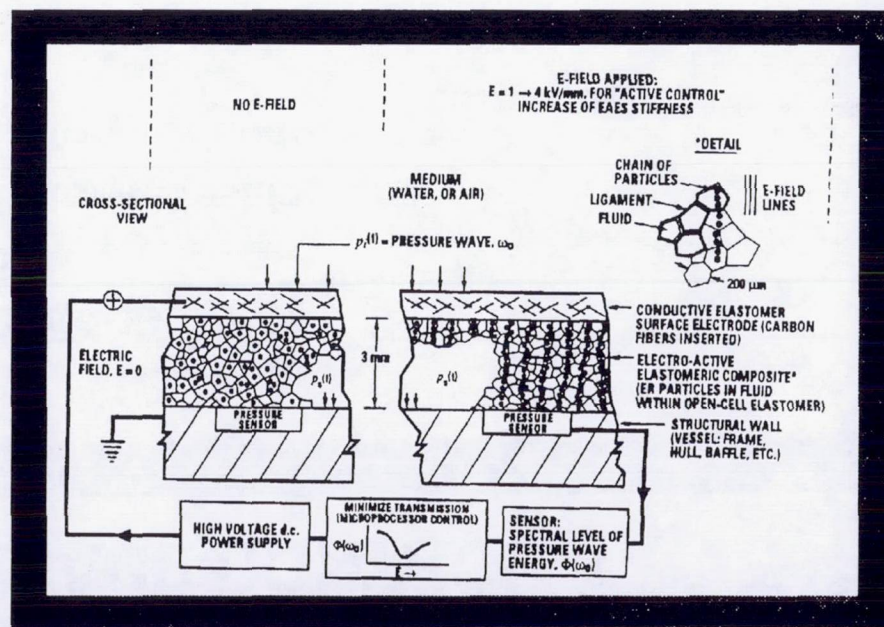
Conductive elastomer composite: (graphite particles + silicone)

Bonded Interface

Electro-active elastomer; (87 wt% ER fluid + 13 wt% silicone elastomer)

- Develop Processing Procedure for Electroactive Elastomer Composites

- Develop Acoustic Control Implementation
 - Acoustic isolation of hull-mounted sonar
 - Wavenumber filter for flow noise control





ELECTRO-ACTIVE ELASTOMERIC STRUCTURES FOR HYDROACOUSTIC APPLICATIONS



- **Participating Organizations**

- General Atomics
- Naval Undersea Warfare Center
- Er Fluid Development Ltd.

- **Point of Contact**

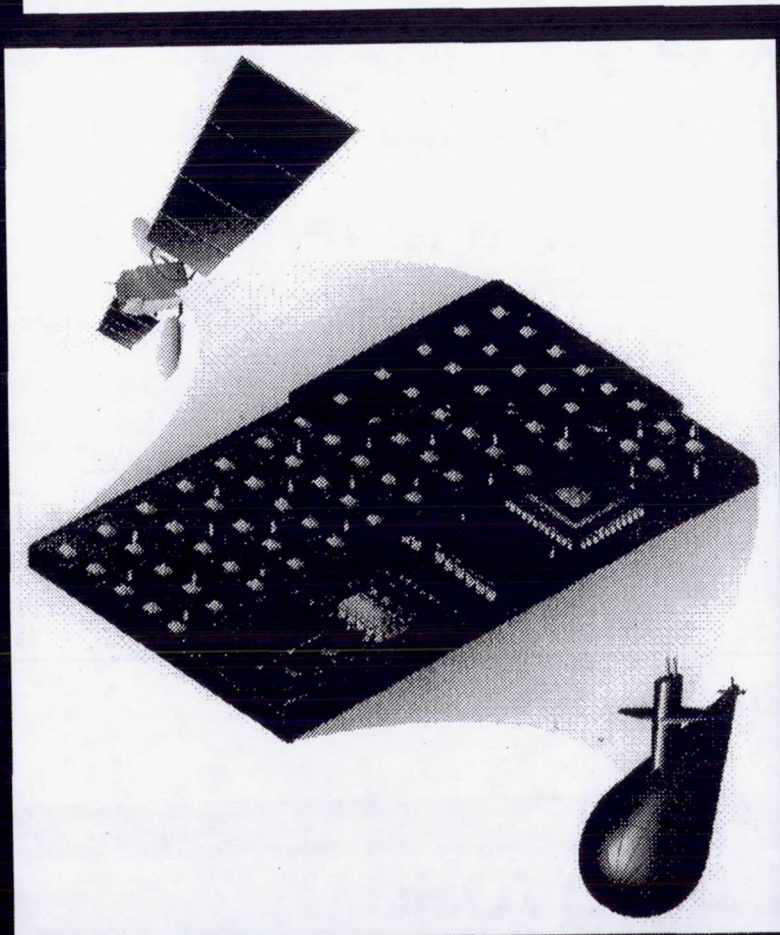
- Dr. Terry D. Gulden
- General Atomics
- (619) 455-2893

- **Funding Profile (\$K)**

<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
300	300	118



COMPOSITE SMART MATERIALS FOR DEFENSE / DUAL-USE APPLICATIONS



- **Composite Materials Development for Undersea Quieting**
 - Develop Design Tools
 - Develop Multi-Layer PMN Electrostrictive Actuators and Sensor Development
 - Integration of Actuators, Sensors, Electronics, Power
- **Test Integrated Panels**
 - Characterize Composite
 - Determine Acoustic Performance



COMPOSITE SMART MATERIALS FOR DEFENSE / DUAL-USE APPLICATIONS



- **Participating Organizations**

- Martin Marietta Technologies, Inc.
- AVX, Inc.
- Naval Research Laboratories
- Virginia Tech

- **Point of Contact**

- Dr. Arthur V. Cooke
- Martin Marietta Laboratories
- (410) 204-2354

- **Funding Profile (\$K)**

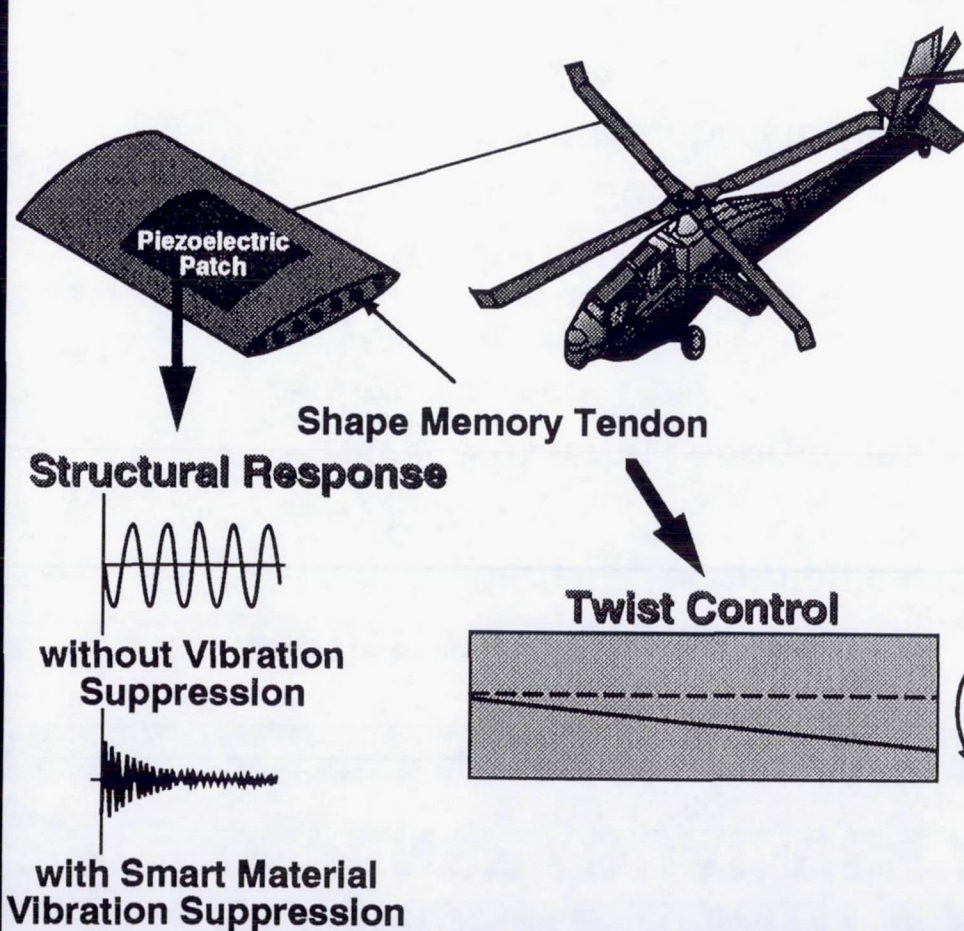
<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
800	1025	1000



SMART MATERIALS AND STRUCTURES



Helicopter Blade Vibration Suppression and Twist Control



Requirements

Vibration Suppression:

Response: 1-100 Hz

Displacement: μ

Twist Control: (Blade Trimming)

Response: Static to 12 Hz

Displacement: mm

Payoffs

Increased Speed (from 160 to 200 Knots)

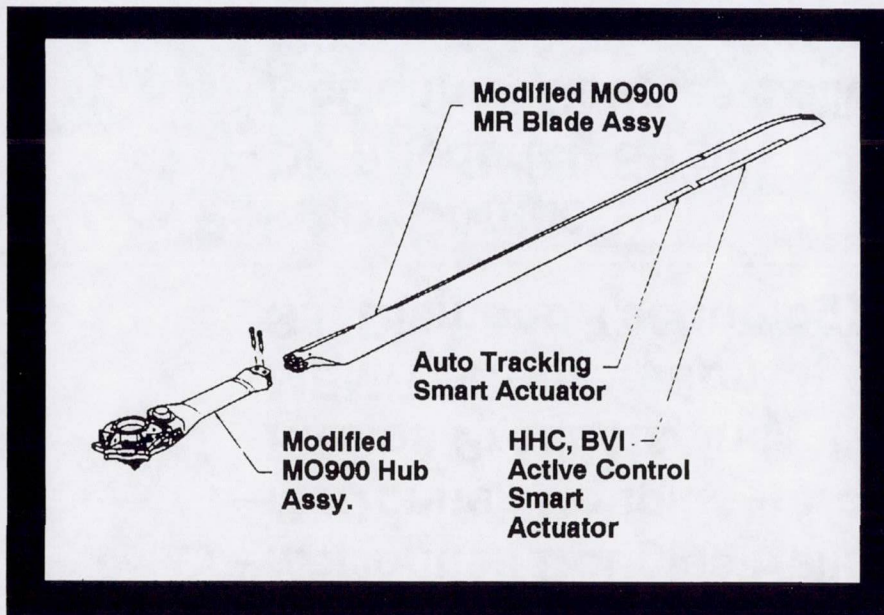
Increased Readiness of at least 15%

Increased Range

Increased Maneuverability



SMART MATERIALS ACTUATOR ROTOR TECHNOLOGY



- **Conceptual Blade Designs for In-Flight Blade Tracking**
- **Actuator & Sensor Integration**
- **Control of In-Flight Blade Tracking**
- **Fabrication of Active Blade**
- **Test of Froude Scale Model**
- **Test of Blades in Wind Tower**



SMART MATERIALS ACTUATOR ROTOR TECHNOLOGY



- **Participating Organizations**

- McDonnell Douglas Helicopter Systems
- McDonnell Douglas Aerospace Corporation East
- Etrema Products, Inc.
- MEMRY Corporation
- S.I. Diamond Technology, Inc.

- **Point of Contact**

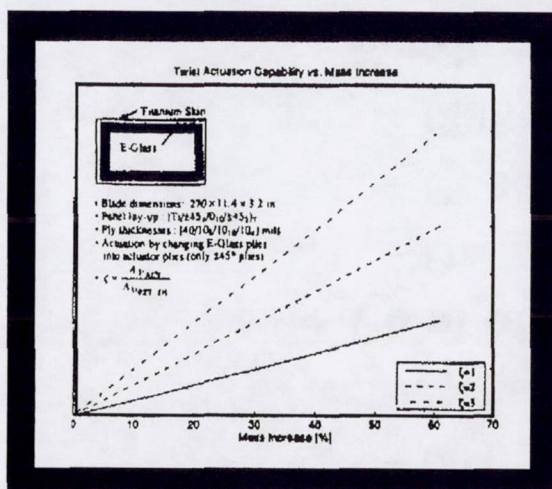
- Dr. Friederich Straub
- McDonnell Douglas Helicopter Systems
- (602) 891-6058

- **Funding Profile (\$K)**

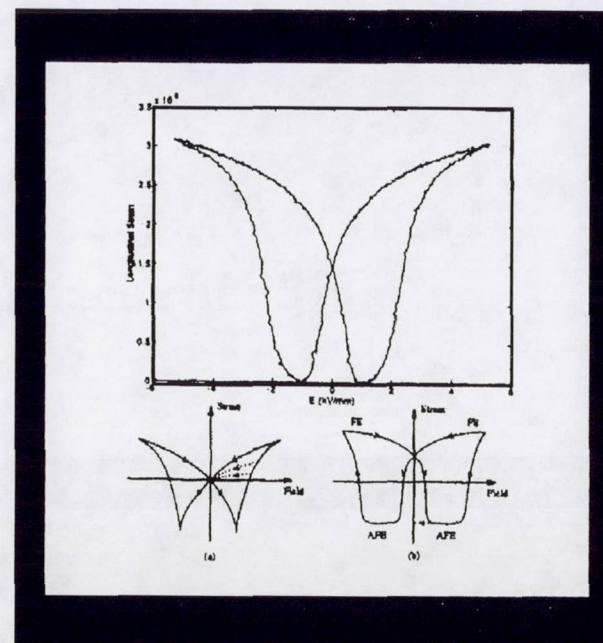
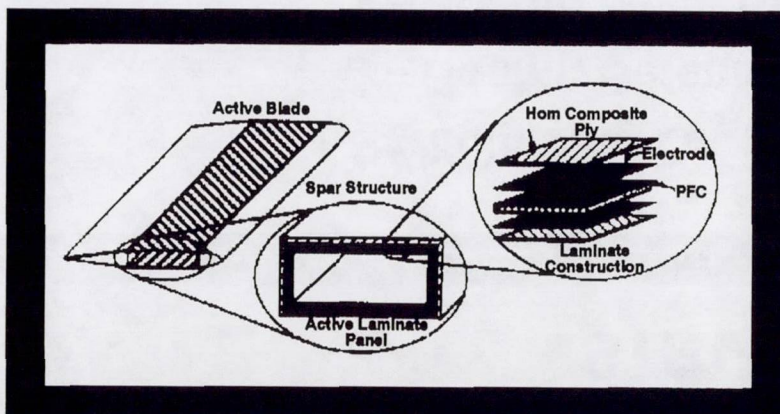
<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>	<u>FY 97</u>
740	1230	1480	250



SMART MATERIALS FOR ROTOCRAFT STRUCTURES



- Shape Memory Ceramic Materials Development
- Structural Design/Analysis of Smart Blade
- Develop Integral Blade Application





SMART MATERIALS FOR ROTOCRAFT STRUCTURE

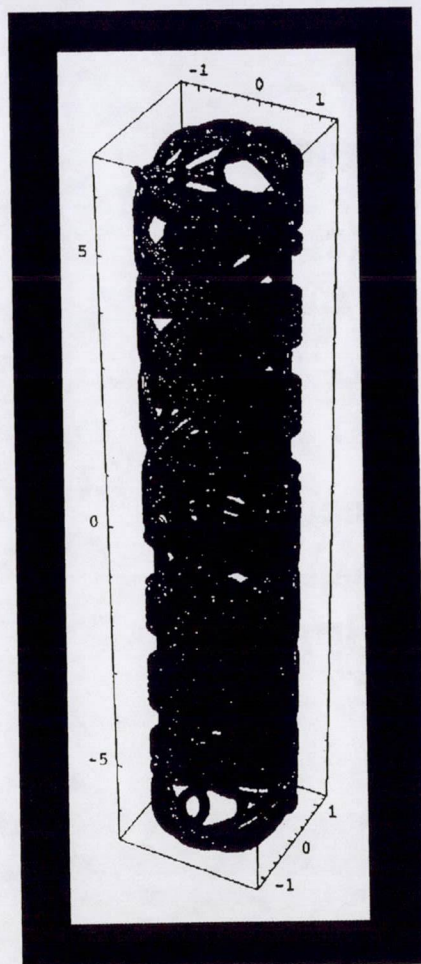


- **Participating Organizations**
 - Boeing Defense and Space Group
 - Boeing helicopters
 - MIT
 - Penn State University
- **Point of Contact**
 - Dean Jacot
 - Boeing Defense and Space Group
 - (206) 773-8629
- **Funding Profile (\$K)**

FY 94	FY 95	FY 96	FY 97
609	650	600	386



THE OPTIMAL DESIGN OF STRUCTURES INCORPORATING "SMART MATERIALS"



- Develop Material Design Technique That Incorporates Variable Physical Tensor Fields - Optimization
- Develop Theory of Structural Sensors Using Finite Length Measurement Paths
- Apply Theory to Helicopter Torque Tube



THE OPTIMAL DESIGN OF STRUCTURES INCORPORATING "SMART MATERIALS"



- **Participating Organizations**

- University of Michigan
- Boeing Defense & Space Group

- **Point of Contact**

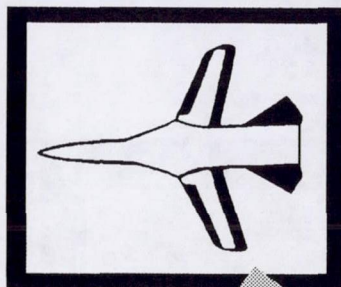
- Dr. P. D. Washabaugh
- University of Michigan
- (313) 763-1328

- **Funding Profile (\$K)**

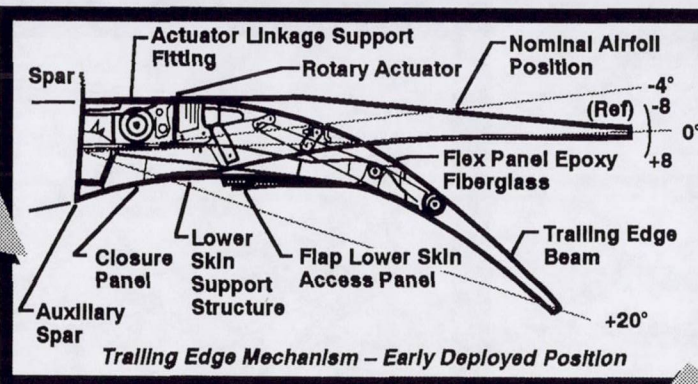
<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
138	150	200



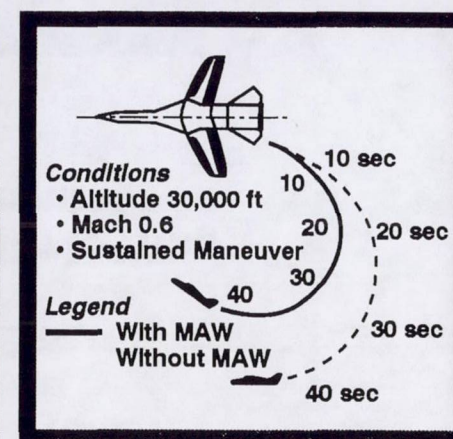
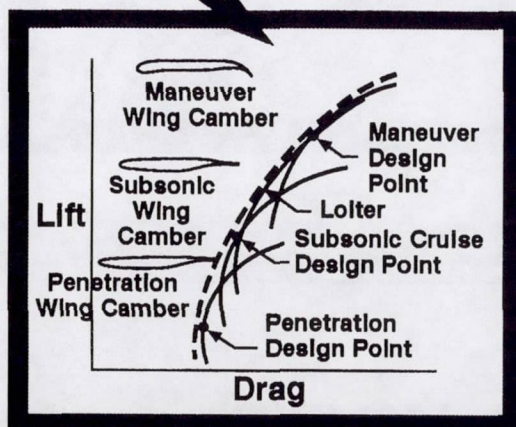
SMART MATERIALS AND STRUCTURES



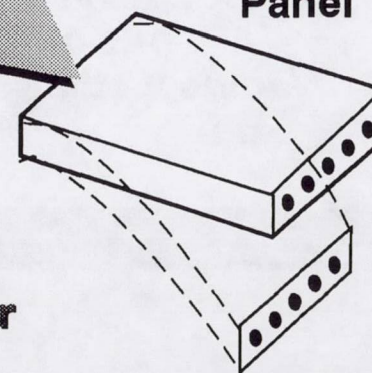
Adaptive Control Surface



Variable Camber Envelope



Adaptive Panel

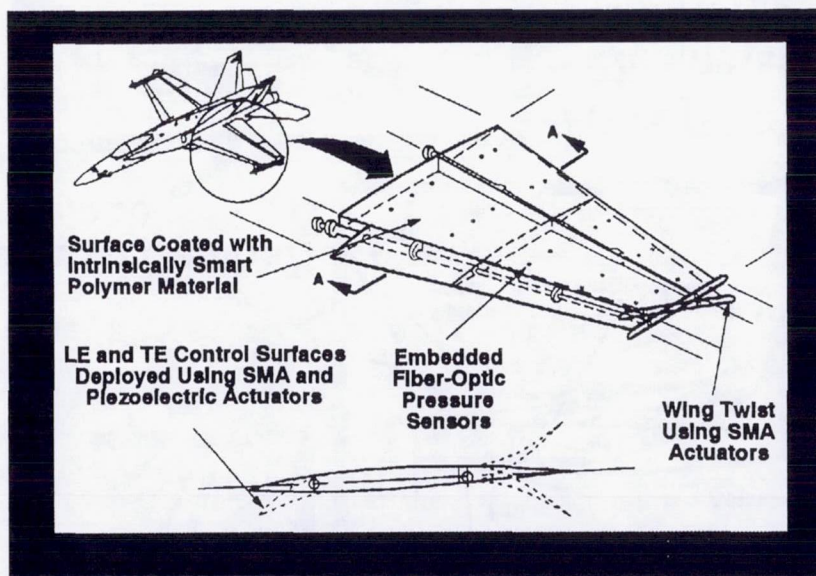


PAYOFFS

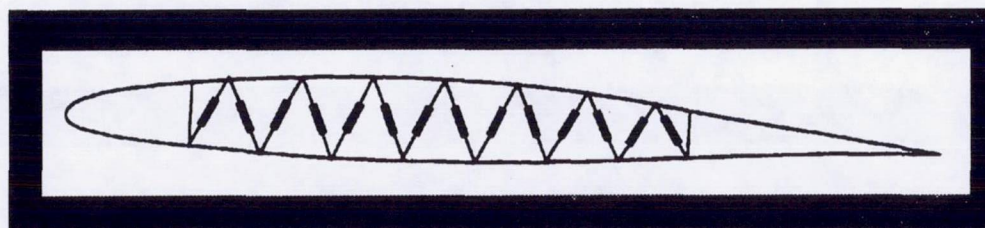
- Eliminates Hydraulics and Hinge Lines
- 30% Higher Payloads
- 50% Longer Range
- 30% Increased Maneuver
- Improved Stealth



SMART WING AND STRUCTURES DEVELOPMENT



- Develop Shape Memory, Piezoelectric and Electrostrictor Actuators
- Develop Fiber Optic Sensor System
- Design Smart Wing
- Demonstrate Wing Subelements





SMART WING AND STRUCTURES DEVELOPMENT



- **Participating Organizations**

- Northrop - Grumman
- Martin Marietta; MNSW, Inc.
- Fiber & Sensor Technologies, Mission Research
- University of California - Santa Barbara, University of Texas-Arlington, Penn State University, NASA Langley Reserach Center

- **Point of Contact**

- J. Kudva
- Northrop - Grumman
- (310) 332-8300

- **Funding Profile (\$K)**

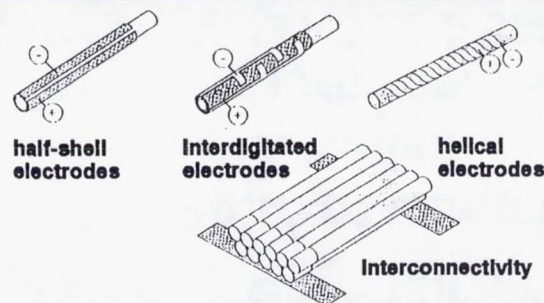
FY 94
1502

FY 95
988

FY 96
920



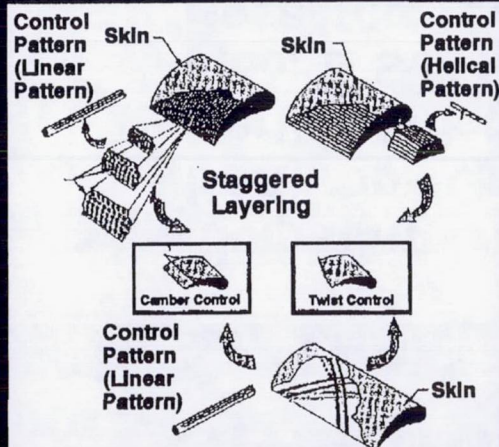
OPTICAL FIBERS FOR ADAPTIVE STRUCTURES SARCOS - SBIR



- Develop Approaches for Design and Fabrication of Active Fibers as Fundamental Sensing & Actuation Components
- Fabricate Generic Adaptive Structure
- Funding (\$K)

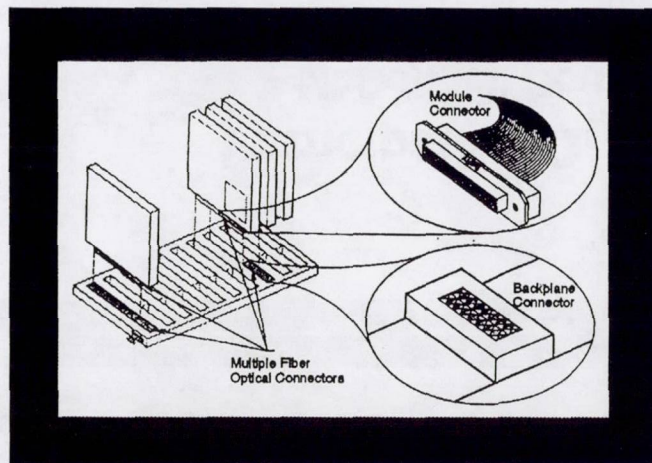
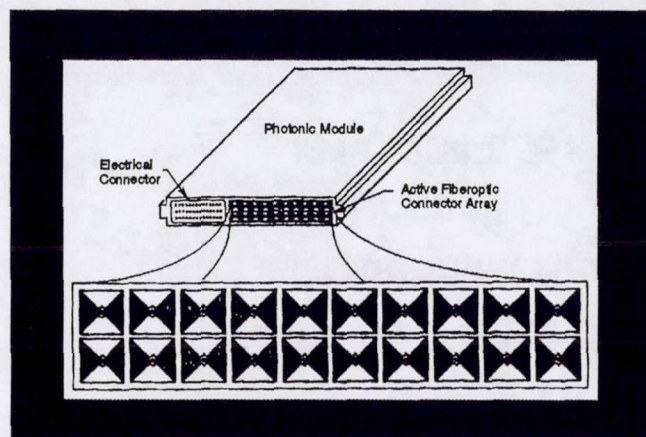
<u>FY 93</u>	<u>FY 94</u>	<u>FY 95</u>
ARPA	50	
Air Force	318	164

- POC: Brian McLean
(801) 581-6499





ACTIVE MATERIALS FOR PHOTONIC SYSTEMS



- **Develop Active Polarization - Preserving Fiber Optic Connector**
- **Modeling of Coupled Fields**
 - Strain
 - Thermal
 - Electrical
 - Optical
- **Design & Fabricate Active Fiberoptic Connector**
- **Demonstrate Prototype Connector**



ACTIVE MATERIALS FOR PHOTONIC SYSTEMS



- **Participating Organizations**

- McDonnell Douglas Aerospace Corporation East
- Metatek, Inc.
- S.I. Diamond Technology, Inc.

- **Point of Contact**

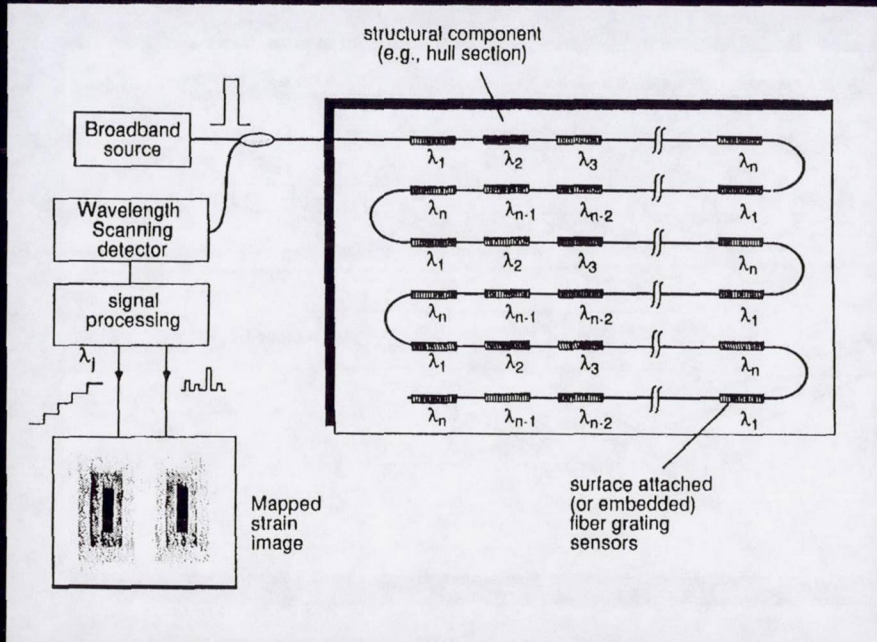
- Dr. John M. Haake
- McDonnell Douglas Aerospace Corporation East
- (314) 234-8661

- **Funding Profile (\$K)**

<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
400	800	800



OPTICAL FIBER SENSORS FOR SMART STRUCTURES NAVAL RESEARCH LAB



•Sensor Technology

- Grating Fabrication Techniques
- Thermal Apparent Strain
- Deformation Sensor (Multi-core)
- High Strain Sensor Concept

•Instrumentation

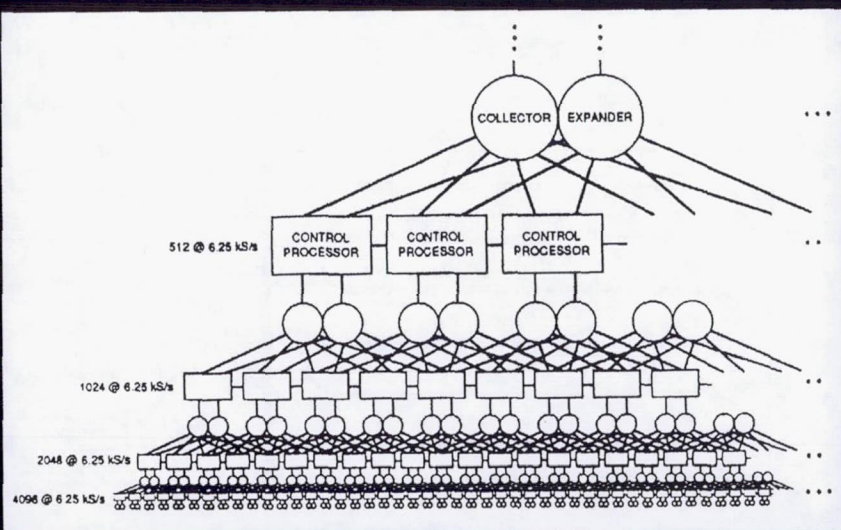
- Point & Integrating Strain Sensor
- High Channel Count FBG Array
- Chirped FBG-based Sensor

•Funding (\$K)

FY 94	FY 95	FY96	FY97
400	500	500	400



CONTROL TECHNOLOGY FOR SMART MATERIALS



- **Develop Design Technology For Sensor / Actuator Placement**
- **Develop Approach For Multiscale Control Scheme**
 - **Controller Architecture**
 - **Redundancy and Fault Tolerance**
 - **Hardware Topology**
- **Demonstrate Control Concepts**
 - **Robustness**
 - **Architecture**
 - **Scalability**



CONTROL TECHNOLOGY FOR SMART MATERIALS



- **Participating Organizations**

- SRI International
- Penn State University

- **Point of Contact**

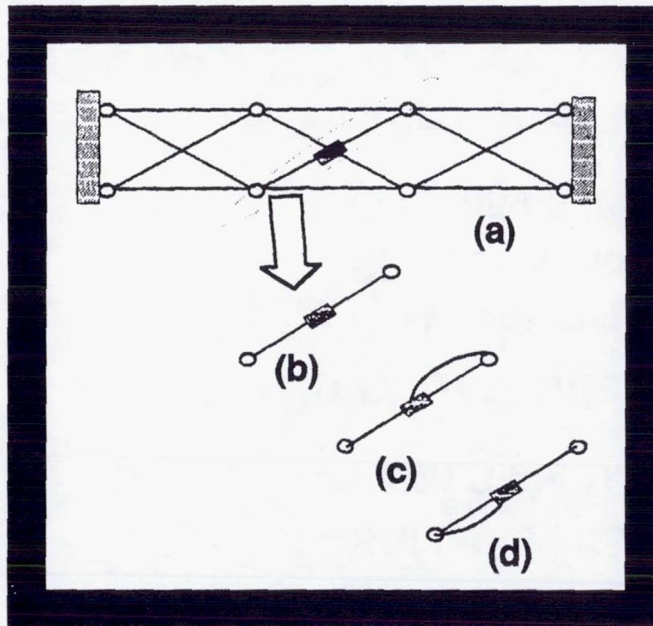
- Dr. David Flamm
- SRI International
- (415) 859-2460

- **Funding Profile (\$K)**

<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
200	400	300



MODAL ENERGY LOCALIZATION QRDC, SBIR



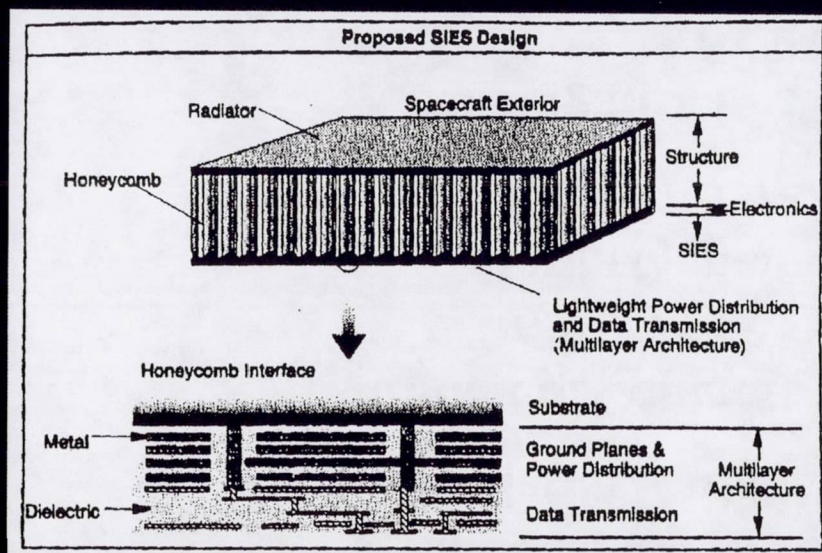
- Theory of Modal Energy Localization
- Application to the Design of Structures
- Experimental Verification of Theory
- Funding (\$K)

<u>FY 94</u>	<u>FY 95</u>
250	250

- POC: Darryoush Allaei



SPACECRAFT INTEGRATED ELECTRONIC STRUCTURES (SIES)



- Develop Modular Integrated Electrical System Into Structural Skin
- Control Signal Design
- Asic Development

- Multi-Level Distribution Panel Fabrication With Mcm Packaging



SPACECRAFT INTEGRATED ELECTRONIC STRUCTURES (SIES)



- **Participating Organizations**
 - Martin Marietta Astronautics Group
- **Point of Contact**
 - Dr. S. Rawal
 - Martin Marietta Technologies, Inc.
 - (303) 971-9378
- **Funding Profile (\$K)**

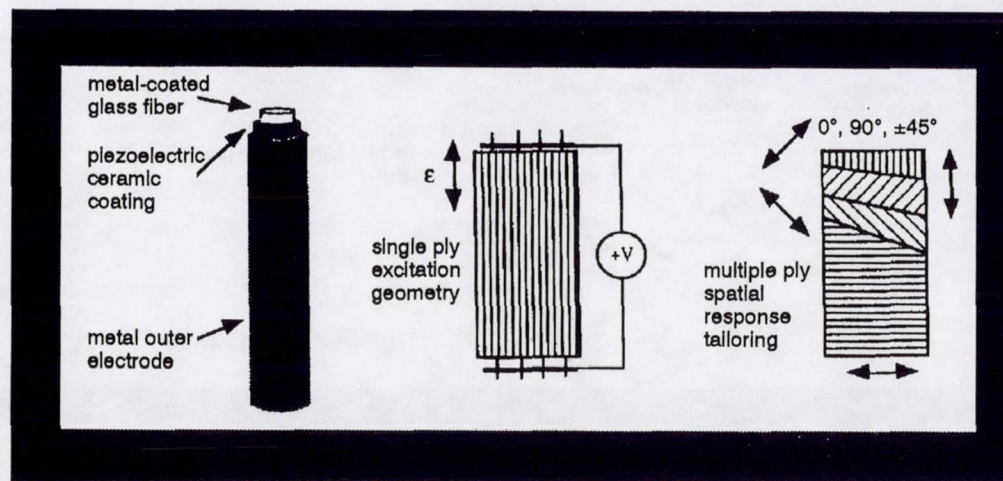
	<u>FY 94</u>	<u>FY 95</u>	<u>FY 96</u>
ARPA	100	350	350
Air Force			
BMDO			



ACTIVE SMA AND OTHER FIBER COATINGS AND FIBER DEVICES F&S TECHNOLOGIES, INC., SBIR



- Develop SMA Coated Fiber
- Develop Absolute Strain, Temperature, & Acoustic Wave Filter Fiber Sensor



- Funding (\$K)

FY 94

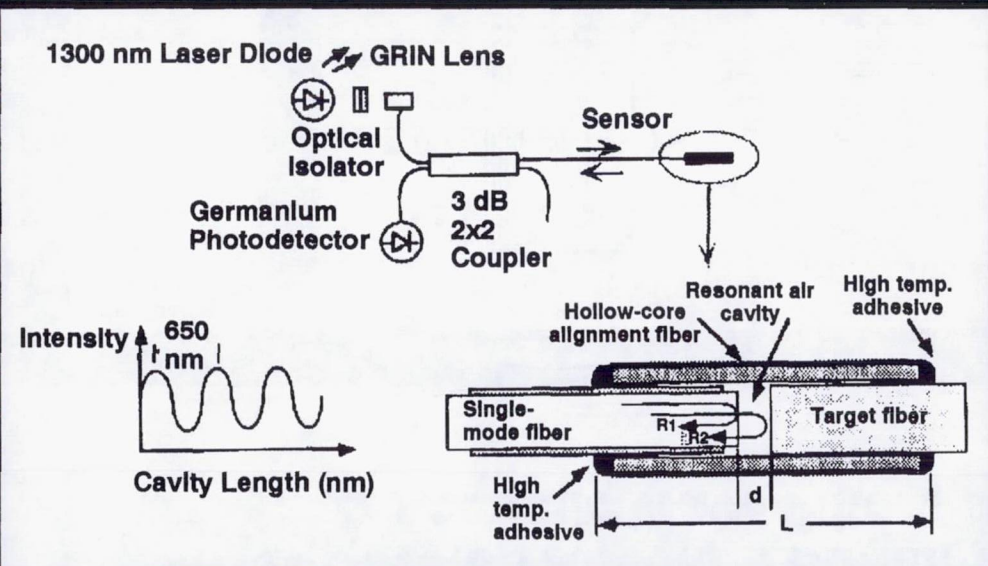
50

- POC:

Kent Murphy
(703) 382-7551



OPTICAL FIBER SENSOR-BASED SMART MATERIALS STRUCTURES F&S TECHNOLOGIES INC/SBIR



- Develop EFPI, SSIB, IFPI Fiber Sensors and Signal Conditioning Electronics
- Develop Embedding & Connecting Techniques

• Funding (\$K)

<u>FY 93</u>	<u>FY 94</u>	<u>FY 95</u>
50	250	250

• POC: Kent Murphy (703) 382-7551



SMART MATERIALS & STRUCTURES

Major Issues



- **THEORIES**
 - Micromechanics
 - Non-Linear Mechanics
 - Cross-Coupled Systems
 - Control
- **DESIGN TOOLS**
 - Materials Response Simulators
 - Multidimensional Data Visualization
 - Interfaces
- **CHARACTERIZATION OF COLLECTIVE BEHAVIOR**
 - Strength
 - Fatigue
 - Durability
- **INTEGRATION**
 - Concurrent Engineering
 - Local/Global Optimization



SMART MATERIALS & STRUCTURES

Major Issues



- **SENSORS**

- Optimization of Figures of Merit re Processing and Microstructures
- Environmental Robustness
- New Sensor Materials

- **ACTUATORS**

- Maximization of Deliverable Energy re Processing and Microstructures
- New Actuator Materials

- **COMPOSITE**

- | | |
|-----------------------------|---------------------|
| – Mechanical Behavior | – Manufacturability |
| – Microstructure Production | – Economical |
| – Interfaces | – Durability |
| – On-Board Data Processing | |
| – Calibration | |



SMART MATERIALS AND STRUCTURES

Manufacturing Issues



- **Smart Materials and Component Synthesis**
 - **Materials Processing**
 - **Material/component architecture**
 - **Models for component placement**
 - **Fixing of component placement during synthesis**
 - **Manufacturing techniques and automation**
 - **Compatibility of sensor/actuator systems with matrices and reinforcements**
 - **Interconnects**
 - **Embedded sensor/actuators must be designed and fabricated for part edges**
 - **Linking sensor /actuators with signal processing system**

Page intentionally left blank

Vibration/Noise Control

Chairperson: Anna McGowan

53-27
61418
235089

5P.

Synopsis

Use of smart structures for control and performance improvement of hypersonic vehicles.

by

James A. August and Dr. Shiv Joshi

Mechanical and Aerospace Engineering Department
University of Texas at Arlington

The objective of this presentation was to point out the fact that there are many promising applications for smart structures technology on hypersonic vehicles. This is not inherently obvious due to the real and perceived operating environments of hypersonic vehicles. Although hypersonic vehicles such as a single stage to orbit (SSTO) aircraft or a military missile do operate in extreme environments as far as temperature and vibration are concerned, there are many areas on these vehicles where smart structures could not only survive, but could improve vehicle performance. In the world of hypersonic vehicles the difference between success and failure can be small enough that this improvement could become very important, not only for cost savings but for the ability of the vehicle to accomplish its mission.

The idea behind this project was to talk to hypersonic vehicle designers and academics to find out what sort of problems could be solved with smart structures. These problems are not necessarily structural in nature, they can involve vehicle dynamics, acoustics, aerodynamics, or thermal problems. The common thread is that these problems are difficult or impractical to solve using current technology. After a variety of problems were outlined an attempt was made to look at each problem in terms of how smart structures might help. Although some of the problems are obviously beyond the current state of the art in smart structures, they were retained in the presentation as a sort of hypersonic vehicle designer wish list.

Two main conclusions could be drawn from this study. One is that the actual environment inside a hypersonic vehicle is not always as severe as it appears. In the larger vehicles such as SSTO, the length of the mission is long but the temperature of much of the vehicle must be kept relatively cool due to current limits of hydraulic actuators, materials limitations, and payload and crew requirements. In the smaller vehicles, such as missiles, the temperatures are allowed to get much higher, but the vehicles flight duration is so short that potential smart structure degradation is not necessarily a limiting factor. Although there are obviously many vehicles and applications that do have operating environments too severe for smart structures, the point is that there are definite

opportunities to use this technology.

The second conclusion is that the hypersonic community needs a different type of research done on a faster timetable in order to use smart structures technology. Vehicle design cycle times are such that a technology must be proven before the vehicle is designed. Once the vehicle is actually in the design phase the managers and senior designers are not inclined to try unproven technology no matter how promising it appears. What this means is that general smart structures solutions for hypersonic vehicles should be researched from current and previous missile and vehicle programs, knowing the the same problems will surely appear again in the next design cycle. A relatively small amount of applied research towards these general problems, done early enough, could allow designers to further develop the technology for use an operational vehicle.

The authors acknowledge:

UTA/NASA Center for Hypersonic Research

Lockheed-Martin Fort Worth Division

Bill Garver

Dr. C.V. Clifton

Loral - Vought Systems

Ronald C. Knight

Dr. B.H. Burzlaff

John H. Miranda

Short Term NASP Smart Structures Applications

Control wing flutter - studies and experiments have been performed at low speeds and ambient temperatures. Research could be extended to high speeds/temperatures.

Reduce acoustic fatigue in critical structures - SCRAMJET inlet will be subjected to high acoustic levels for a long duration. Smart structures could be used to damp out acoustic vibrations in this and other areas. This could result in weight savings and life increase.

Lower acoustic levels experienced by payload and passengers - smart structures could be most easily applied in the ambient temperature environment of the cabin and payload bay to lower acoustic levels.

Control fuel slosh with smart tank - a fuel tank with smart baffles could de-couple the fluid dynamics from vehicle and engine dynamics. This could be used to reduce POGO and also could be used to control vehicle structural dynamics since the fuel fraction is very high. Proposed tank designs use carbon/epoxy composites which must operate at -400°F.

Control coolant flow in skin using constricting SMA tubes - SMA tubes embedded in skin could be used to control flow of liquid hydrogen by constricting at lower temperatures which would reduce flow. Piezoelectric microvalves could also be used to adjust coolant to conserve hydrogen.

Long Term NASP Smart Structures Applications

CTE strain fuse - High stresses due to CTE mismatch in high temperature hypersonic applications could be reduced by SMA strain fuses.

Body flexing to control vehicle attitude - vehicle attitude could be controlled by fuselage bending. A more likely idea is to use bending in certain vehicle locations to de-couple vehicle structural dynamics from engine dynamics and flight control dynamics. This could result in keeping the engine inlet pointed into the airflow more accurately.

185

Use wing flexing to control vehicle attitude - use of wing flexing to control vehicle attitude could reduce weight of conventional control surfaces while including flutter suppression in the design.

Change area of inlet/exhaust of SCRAMJET engine - movable inlet and exhaust could be used to optimize engine performance for various operating conditions. High temperatures and forces make this very difficult.

Control duct acoustics in SCRAMJET engine - smart structures could be used to stabilize inlet flow (especially at inlet lip) to prevent engine unstarts. Small high frequency changes in inlet wall shape may be able to arrest unstarts before they happen. Limited research has been done in subsonic and supersonic duct flow using smart structures.

Smart Structures Improvements to Existing Missile Designs

SMA spacers to reduce fin twist - Fins on some missiles must be free to deploy at launch but must be rigidly fixed during flight. Expensive machining is now needed to match part clearances. SMA spacers could expand at launch to tighten fin joints.

Correct thrust misalignment - Thrust misalignment is a common production flaw that is difficult to detect before missile launch. The missile control system can currently correct this problem but the missile has reduced maneuverability. Smart nozzles castered by piezoelectric actuators would be able to work with the existing control system to vector missile thrust.

Flutter suppression in missile fins - Active flutter suppression may lead to lighter structural weight in some missile designs. Flight loads are small compared to rigidity needed for fin deployment and flutter prevention.

Self arming fuse/munitions deployment - Currently complex electronic fuses are needed to prevent missile arming before launch. SMA embedded in fuselage or similar scheme could be used to arm missile when skin temperature reaches typical flight value.

Replace existing actuators with smart actuators - Linear piezo-electric or magnetostrictive motors could be used to replace existing actuators where space requirements are critical. Currently available rotary actuators often require complex linkage arrangements in some missile designs.

Electrorheological Fluids - Aerospace Applications

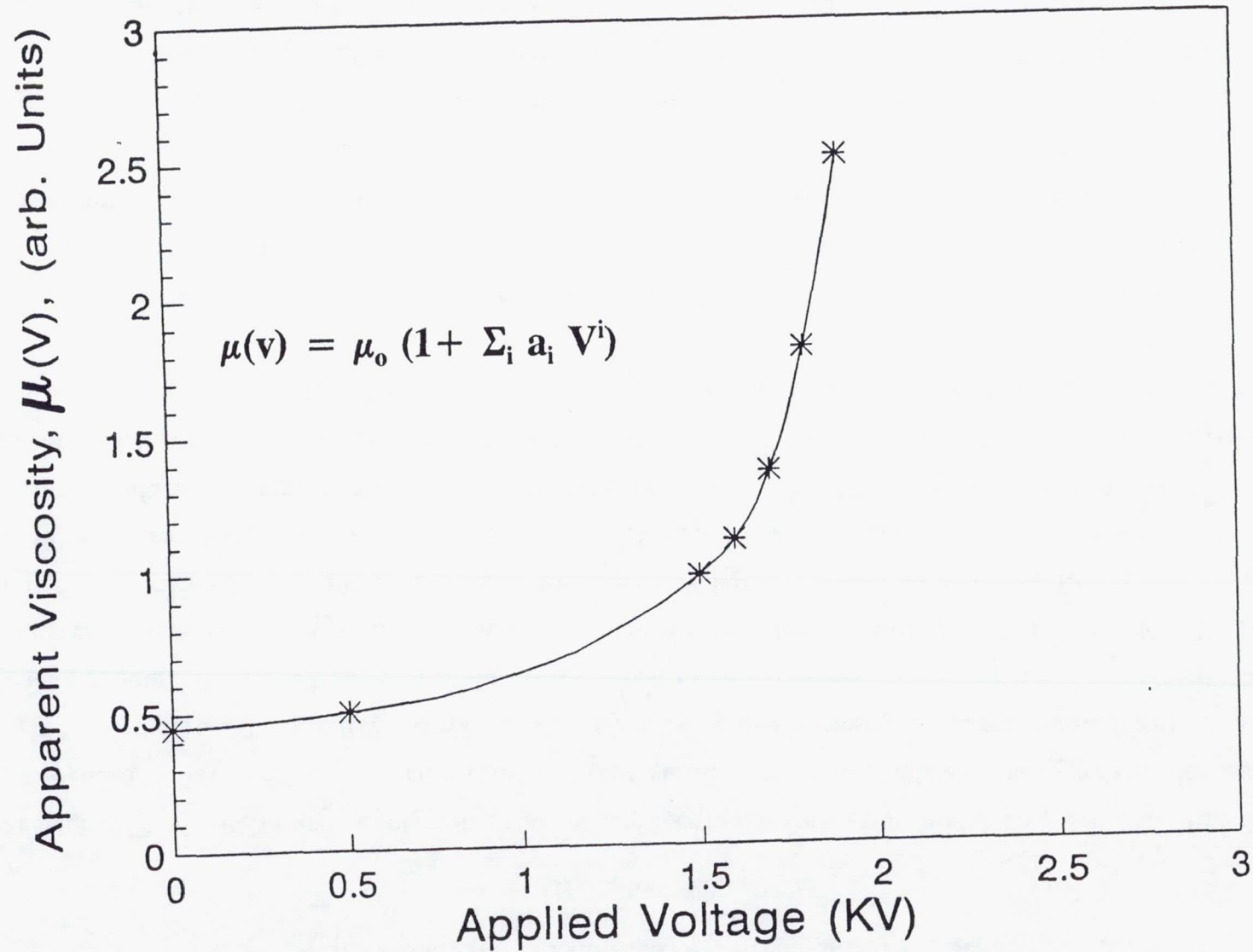
D. S. Parmar, A. Eftekhari, K. W. Belvin and J. J. Singh
NASA Langley Research Center
Hampton, VA.

Electrorheological Fluids (ERF) are an intriguing class of non-Newtonian industrial fluids. They consist of fine dielectric particles suspended in liquids of low dielectric constants. The viscosity of these (particle - liquid) systems depends on the electric field applied across them. After a certain critical field, the system viscosity increases almost asymptotically. In the conventional ER fluids, there are two main problems that must be solved before ERF's can find wide spread applications in the industry: (1) The suspended particles settle down at the bottom after a certain period of zero field. This requires re-suspension of the particles before any further use of the (particle - liquid) system can be made. Re-suspension of the particles can be rendered unnecessary if the densities of the suspended particles and the liquid were equal. (2) The electric field needed to produce an asymptotic increase in the viscosity of the current ER Fluids is of the order of 20 - 30 KV/cm. This field is too high for reasons of the safety for most industrial operations. The critical field needed for asymptotic increase in ERF viscosity can be significantly reduced by a proper selection of the (particle - liquid) combination.

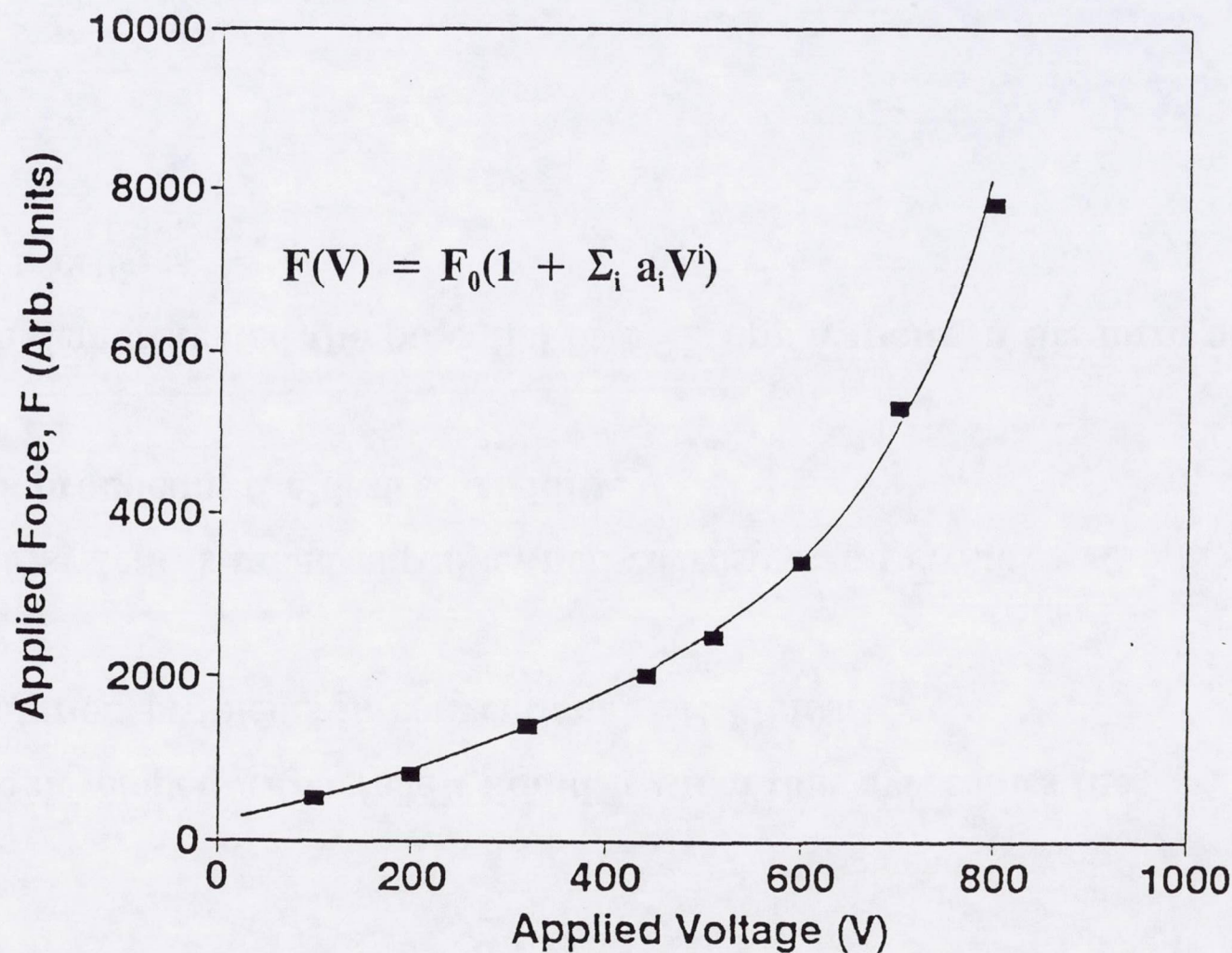
The objectives of this research were to select a particulate system such that: (i) its density can be varied to match that of the selected liquid, and (ii) the dielectric constant of the particles and the liquids should be such that the critical fields needed for asymptotic increase in viscosity are ≤ 10 KV/cm. Synthetic Zeolite particles were selected as solute/suspensions. These Zeolite particles are mostly hollow and can be charged with appropriate amount of the solvent (fluid) to make their density equal to that of the fluid. Octoil oil was selected as the solvent. The (Zeolite-Octoil oil) system is non-corrosive and requires electric fields of less than 10 KV/cm to produce dramatic increase in the viscosity of the ERF and the critical shear stress needed to initiate relative motion between the two plates of the ERF sandwich. The results are summarized in the following figures.

54-27
61420
235090
4/8

EFFECT OF APPLIED ELECTRIC FIELD ON THE VISCOSITY OF THE ER FLUID



EFFECT OF APPLIED ELECTRIC FIELD ON CRITICAL SHEAR STRESS



SUMMARY

- We have developed a (particle - liquid) system that overcomes the sedimentation problems in conventional ER Fluids.
- The ERF system studied is stable, non-corrosive and requires < 5 KV/cm field for producing the desired rigidity.
- We have demonstrated the potential of ERF applications in the form of thin sandwich cells.

The Piezoelectric Aeroelastic Response Tailoring Investigation

Anna-Maria Rivas McGowan
Aeroelasticity Branch - NASA Langley Research Center

55-27

61422

235091

6P.

The Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI), a joint program between the NASA Langley Research Center and the Massachusetts Institute of Technology, was developed with the goal of advancing the state of the art in applying piezoelectric actuators to aeroelastic systems. In recent years, there has been considerable effort in investigating active control of aeroelastic phenomenon using piezoelectric actuation. A summary of this work was compiled by Weisshaar who also provides a considerable reference list.¹ Experimental study in this area has primarily focused on reduced-order models. The PARTI program was the first study using a relatively large, multi-degree-of-freedom aeroelastic testbed. During this program a wind-tunnel model was designed and fabricated, aeroservoelastic analyses were performed and the model was ground and subsequently wind-tunnel tested. Studies which laid the groundwork for the design and fabrication of the PARTI wind-tunnel model have been detailed by Lin and Crawley.² The main objectives of this program are to develop detailed analytical and experimental techniques and demonstrate the ability of strain actuated adaptive wings to affect aeroelastic control.

The PARTI wind-tunnel model is a five-foot long, transport style wing that was designed to flutter at low speeds to simplify aerodynamic analyses and wind-tunnel testing. The flutter speed of this model is approximately 260 fps. The major components of the model are shown in Figure 1. The model consists of two primary structures: and exterior fiberglass shell used to obtain aerodynamic lift; and, an interior composite plate that contains the piezoelectric actuators and acts as the main load carrying member. The interior plate is composed of an aluminum honeycomb core sandwiched by graphite epoxy plates. The plates are of $[20^{\circ}_2/0^{\circ}]_s$ laminate, referenced to the wing's quarter-chord which is swept 30° . The non-anti-symmetric composite lay-up provides a static coupling of the bending and torsional behavior. Aeroelastic coupling of the bending and torsional characteristics is provided by this static effect as well as the wing sweep. Fifteen groups of piezoceramic actuator patches are adhered to the top and bottom of the interior plate. As shown in Figure 1, the actuators are configured to impart moments to the plate; however, the ply orientation of the graphite epoxy and the wing sweep angle make it possible for piezoelectric actuation to affect both the bending and torsion natural modes of the model. Loads on the model were monitored using ten strain gauges and four accelerometers. In addition to the piezoelectric actuators, the model has a trailing edge aerodynamic control surface. Also, a flutter stopper-tip mass ensemble was constructed as a safety device for wind-tunnel testing. The complete design of the PARTI model is documented by Reich and Crawley.³

The development of the aeroelastic equations of motion began with a finite element model developed in NASTRAN. Ground vibration test results were used to tune the mode shapes, natural frequencies and structural dampings of all configurations. An analytical state-space model of the PARTI wind-tunnel model is being developed to serve as a plant for control law design at unstable conditions, to verify piezoelectric modeling techniques and to serve as the basis for future analytical studies. The linear aeroelastic equations of motion were developed using the Integration of Structures, Aerodynamics and Controls Code (ISAC).⁴ The doublet lattice technique⁵ was used to calculate the subsonic generalized aerodynamic forces due to wing motion and gusts.

The PARTI wind-tunnel test program consisted of two entries in the Transonic Dynamics Tunnel at NASA Langley. The first test was an open-loop test conducted in March 1994. The primary purpose of this test was to determine plant characteristics for control law design at subcritical speeds and to verify analytical models. This was accomplished by obtaining time history data that was used for transfer function and state-space model calculations and by experimentally determining flutter speeds and frequencies. To acquire time history data, each of the 15 piezoelectric actuator groups was activated individually, as well as in five sets of several actuator groups. State-space models generated from the experimental time history data were used as plants

for control law design at subcritical design conditions and for actuator grouping studies. The data acquired during the test were used in several forms: time histories, transfer functions and state-space models. The second wind-tunnel test was a closed-loop test conducted in November 1994. During this test, 28 control laws were tested to investigate flutter suppression and reduced response at subcritical speeds. Examples of two control laws and the open and closed loop results are shown in Figures 2 and 3. Both of the control laws depicted successfully increased flutter dynamic pressure and reduced aeroelastic response at subcritical speeds. Further discussion of the control law design methods and effectiveness is given by Lin, Crawley and Heeg.⁶

The future plans for the PARTI program include additional wind-tunnel testing, laboratory testing and analytical work. Future wind-tunnel test plans focus on using the PARTI model as a testbed for neural network controllers. The goal of the program is to integrate the expertise of NASA, industry and academia to provide a successful wind-tunnel test demonstration of adaptive neural control technology. The objectives of laboratory testing include: determining the power consumption of the piezoelectric actuators while controlling the response of the structure; investigating optimal piezoelectric actuator placement; and, testing disturbance rejection controllers at zero airspeed. Analytical studies will seek to improve mathematical modeling methodologies.

This research effort has resulted in the design, fabrication and aeroelastic analysis and testing of a five-foot span wind-tunnel model equipped with piezoelectric actuators. Ground vibration testing was conducted to verify the in-vacuo characteristics of the model and the results used to refine the finite element model. An open-loop wind-tunnel test took place in March 1994. System identification data and flutter dynamic pressures were obtained. These experimental data were used to generate state-space models using a time-domain system identification technique. Additionally, the experimental data served as a verification tool for analytical techniques. A closed-loop wind-tunnel test, conducted in November 1994, accomplished the goals of demonstrating increased flutter dynamic pressure and subcritical response tailoring with piezoelectric actuation. Results of these tests will also be used to improve mathematical modeling techniques and examine scaling a piezoelectric actuation system for a full-scale aircraft.

References:

- 1 Weisshaar, T.A., *Aeroservoelastic Control Concepts with Active Materials*, Proceedings of the 1994 ASME Winter Meeting, November 1994.
- 2 Lin, C.Y. and Crawley, E.F., *Strain Actuated Aeroelastic Control*, SERC#2-93, Massachusetts Institute of Technology, February 1993.
- 3 Reich, G.W. and Crawley, E.F., *Design and Modeling of an Active Aeroelastic Wing*, SERC#4-94, Massachusetts Institute of Technology, February 1993.
- 4 Adams, W.M. and Hoadley, S.T., *ISAC: A Tool for Aeroservoelastic Modeling and Analysis*, NASA TM-109031, 1993.
- 5 Giesing, J.P., Kalman, T.P., and Rodden, W.P., *Subsonic Unsteady Aerodynamics for General Configurations, Part I. Direct Application of the Nonplanar Doublet Lattice Method.*, AFFDL-TR-71-5, Volume I, November 1971.
- 6 Lin, C.Y., Crawley, E.F., and Heeg, J., *Open Loop and Preliminary Closed Loop Results of a Strain Actuated Active Aeroelastic Wing*, AIAA/ASME/ASCE/AHS/ASC 36th Structures, Structural Dynamics, and Materials Conference, April 1995.

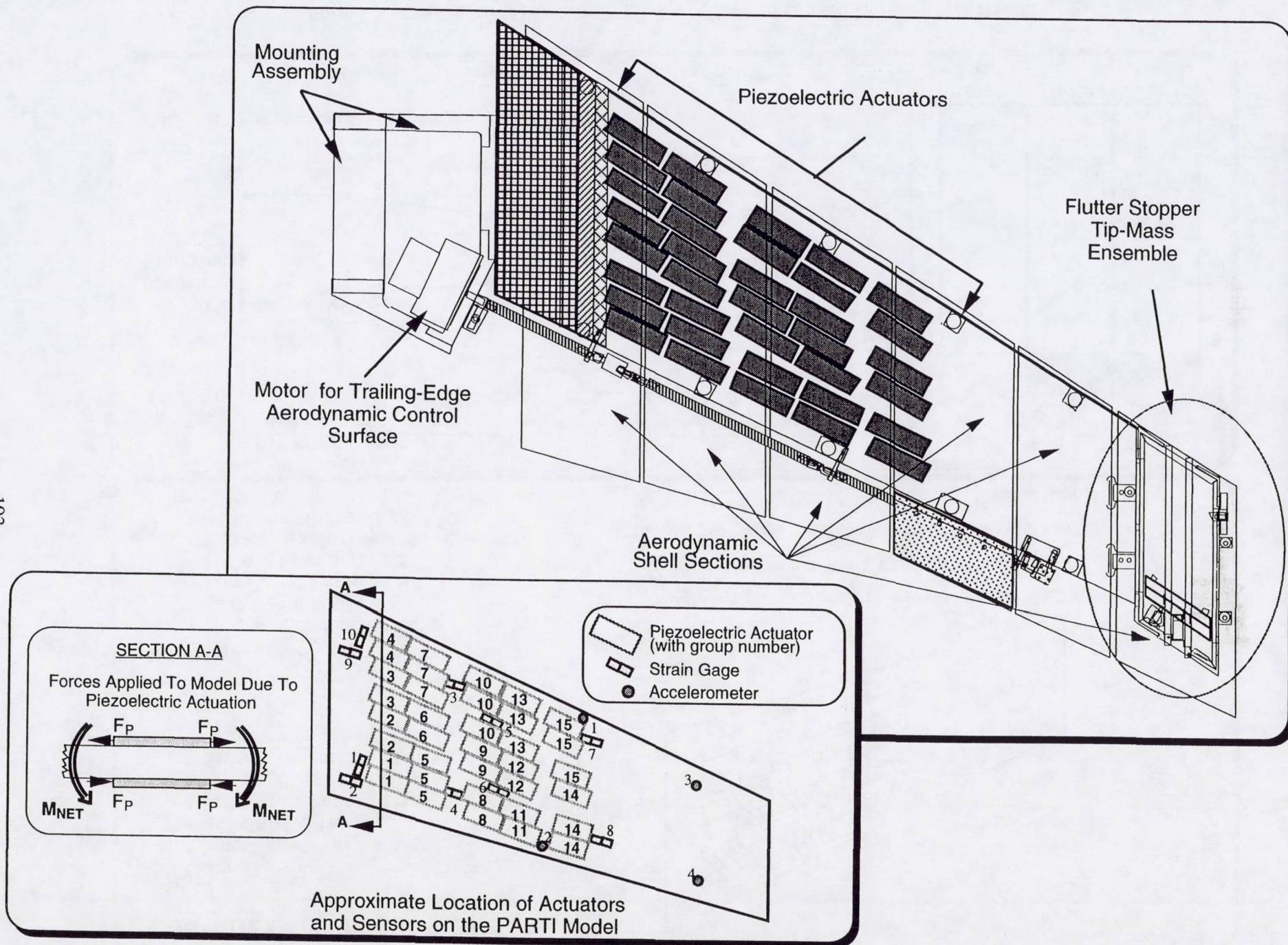


Figure 1: Description of PARTI Model

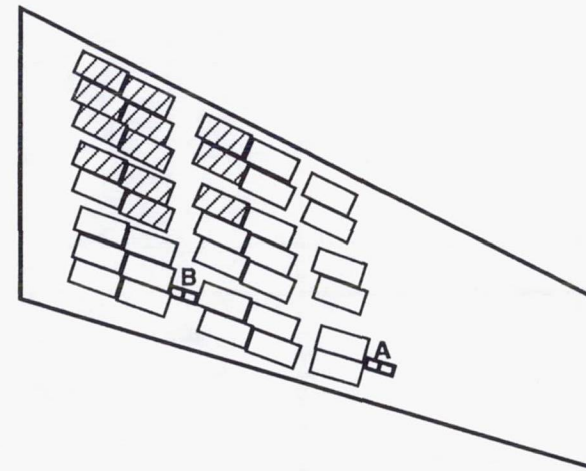
CONTROL LAW DESCRIPTIONS

Control Law A:

- Single-Input, Single-Output
- 6 State LQG Design
- Low Pass Filter at 50 Hz
- Hi Pass Filter at .01 Hz
- Sensor: Strain Gauge 8
- Actuators: All 15 Piezos

Control Law B:

- Single-Input, Single-Output
- Gain Feedback
- Low Pass Filter at 50 Hz
- Hi Pass Filter at .25 Hz
- Sensor: Strain Gauge 4
- Actuators: Piezos 3,4,6,7,10



All Piezoelectric actuators used in Control Law A

Piezoelectric actuators used for Control Law B

Strain gauge used for feedback in Control Law A

Strain gauge used for feedback in Control Law B

FLUTTER RESULTS

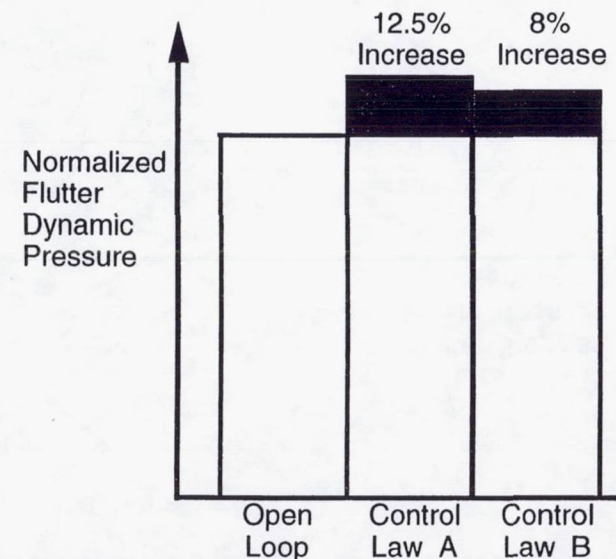
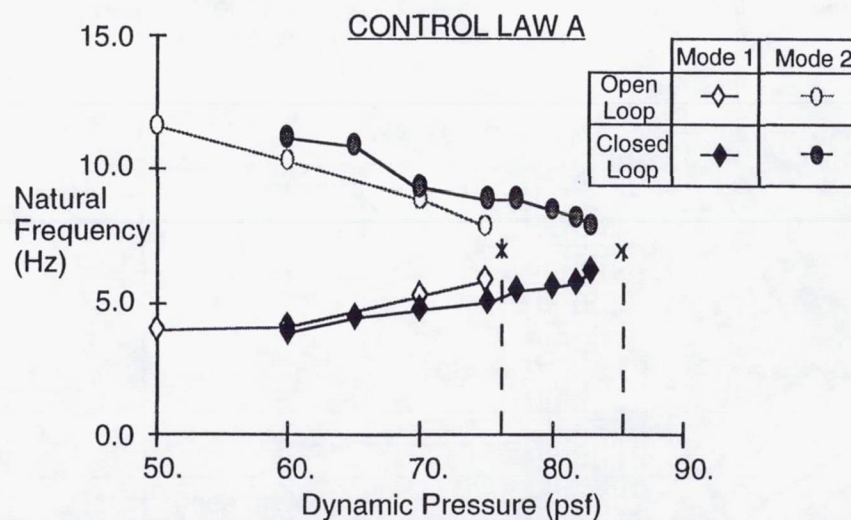
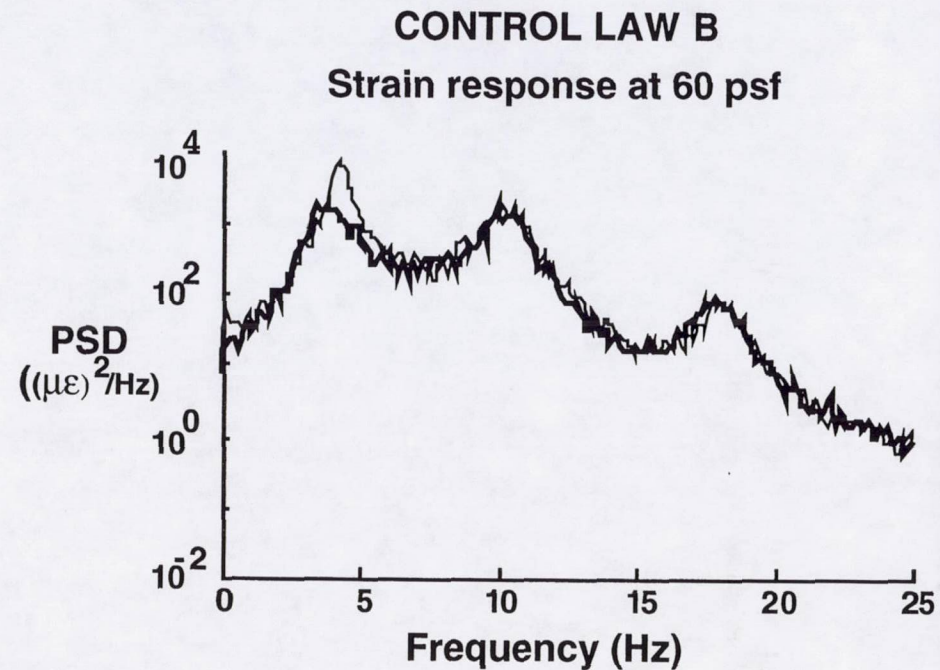
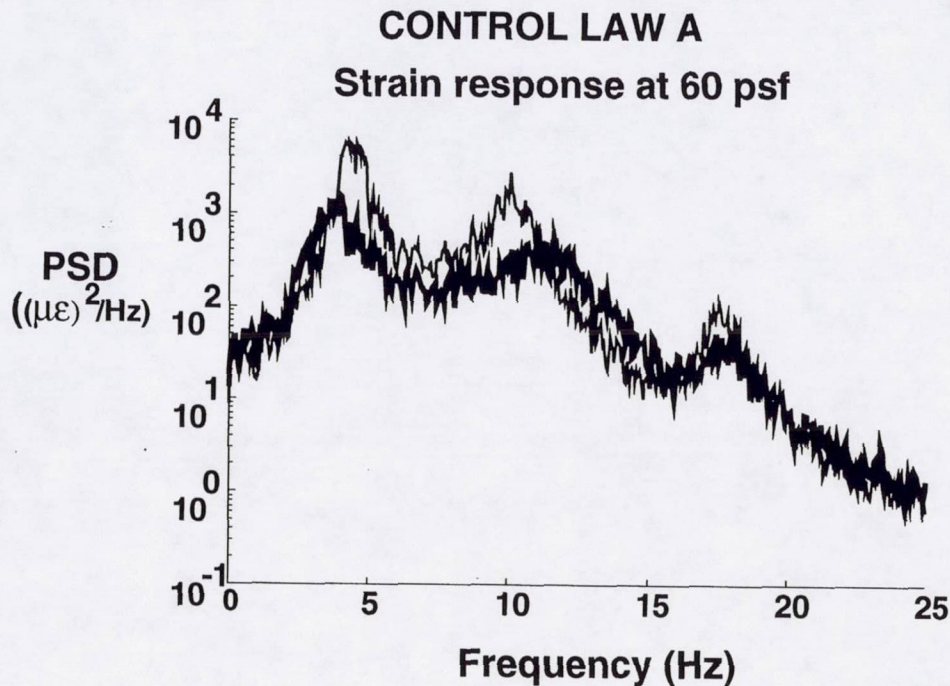


Figure 2: Control Law Descriptions and Open and Closed Loop Flutter Results

SUBCRITICAL RESPONSE TAILORING RESULTS



— Open Loop
— Closed Loop

Control Law A:

- Peak Response Reduced by 75% Compared to Open Loop Value
- RMS Response Reduced by 70%

Control Law B:

- Peak Response Reduced by 75% Compared to Open Loop Value
- RMS Response Reduced by 21%

Figure 3: Subcritical Aeroelastic Response Tailoring Results

Page intentionally left blank

56-27
61425
235092
61.

**Control of Thermal Deflection, Panel Flutter and Acoustic
Fatigue at Elevated Temperatures Using Shape Memory Alloys**

Chuh Mei and Jen-Kuang Huang
School of Aerospace and Mechanical Engineering
Old Dominion University
Norfolk, VA 23529-0247

The High Speed Civil Transport (HSCT) presently under development will cruise at Mach 2.2 to 2.4. Estimated skin-panel temperature will reach 350°F at cruise due to aerodynamic heating. Thus, the structure will have to be designed to withstand high aerodynamic load at supersonic speeds (panel flutter) and high acoustic load (acoustic or sonic fatigue) due to fluctuating boundary layer or jet engine acoustic pressure. The thermal deflection of the skin panels will also alter the vehicle's configuration, thus it may affect the aerodynamic characteristics of the vehicle and lead to poor performance.

Shape memory alloys (SMA) have a unique ability to recover large strains completely when the alloy is heated above the characteristic transformation (austenite finish T_f) temperature. During the recovery process, large recovery stresses occur if the SMA wire is restrained. There are also large increases in Young's modulus and yielding stress. Nickel-titanium alloys (Nitinol) are the most common SMA. The recovery stress and elastic modulus are both temperature dependent, and the recovery stress also depends on the initial strain.

The elastic modulus for Nitinol is 4 Msi at low temperature and only 12 Msi at high temperature which is comparable with Kevlar ($E_1=11$ Msi) and much smaller than graphite/epoxy ($E_1=20$ Msi) composite lamina. Thus, even the elastic modulus of SMA is increased three times at higher temperatures, it has no real gain in structural strength as compare with conventional composite laminates (such as graphite/epoxy).

An innovative concept is to utilize the recovery stress by embedding the initially strained SMA wire in a graphite/epoxy composite laminated panel. The SMA wires are thus restrained and large inplane forces are induced in the panel at elevated temperatures. Using the Nitinol recovery stress data as an illustration, if 10% of the graphite fibers in a 20x20x0.050 in. graphite/epoxy laminated panel (1 in². cross-section) are replaced by Nitinol wires with 4% initial strain, the inplane force will be of 4,000 lbs if uniaxial ($N_x=200$ lb/in.) or 2,000 lbs bi-axial ($N_x=N_y=200$ lb/in.). This large inplane tensile force in the panel at 350°F cruise temperature will be certainly beneficial for HSCT to reduce thermal deflection and vibration. First, the critical buckling temperature of the skin panels will be increased. If the panel critical buckling temperature can be raised higher than the skin-panel temperature at cruise (350°F), then large thermal postbuckling deflection can be completely eliminated. Thus the vehicle can maintain the same optimal aerodynamic configuration at high temperatures as at the low or ambient temperature. Secondly, the dynamic responses of the skin-panels due to supersonic aerodynamic load (panel flutter) and random excitation of boundary layer or jet noise load (acoustic response) can be drastically reduced. This would enhance the vehicle's service life.

Slide 1 shows the maximum thermal postbuckling deflection for a laminate with no SMA and with 10% SMA fibers and 3% initial strain. The plate deflects not until the temperature is high than the first low critical temperature. As the temperature is greater than the austenite start temperature T_s , the shape memory effect is active thus the deflection is decreased. The plate deflection is eventually reduced to zero and the plate remains flat until the second higher critical temperature is reached. As the temperature is greater than the second critical temperature, the plate deflects again.

The thermal postbuckling deflection can be completely eliminated within the operating temperature range of the structure. Using the HSCT as an example, the operation temperature range for the skin panels is estimated to be between -30°F and 350°F. The alloy composition in shape memory metals determines primarily the transformation temperature. Varying the nickel content by 3 weight percent can change the transformation temperature of Nitinol by as much as 378°F (-58°F to 320°F). To remove the first thermal deflection response is thus simply to have the proper alloy composition. To eliminate the second thermal deflection response within the operating temperature range, this can be accomplished by having proper percentages of SMA volume fraction and initial strain such that the second higher critical buckling temperature is greater than the maximum operating temperature (that is $\Delta T_{cr} > 280^\circ\text{F}$ or $T_{cr} > 350^\circ\text{F}$ for HSCT).

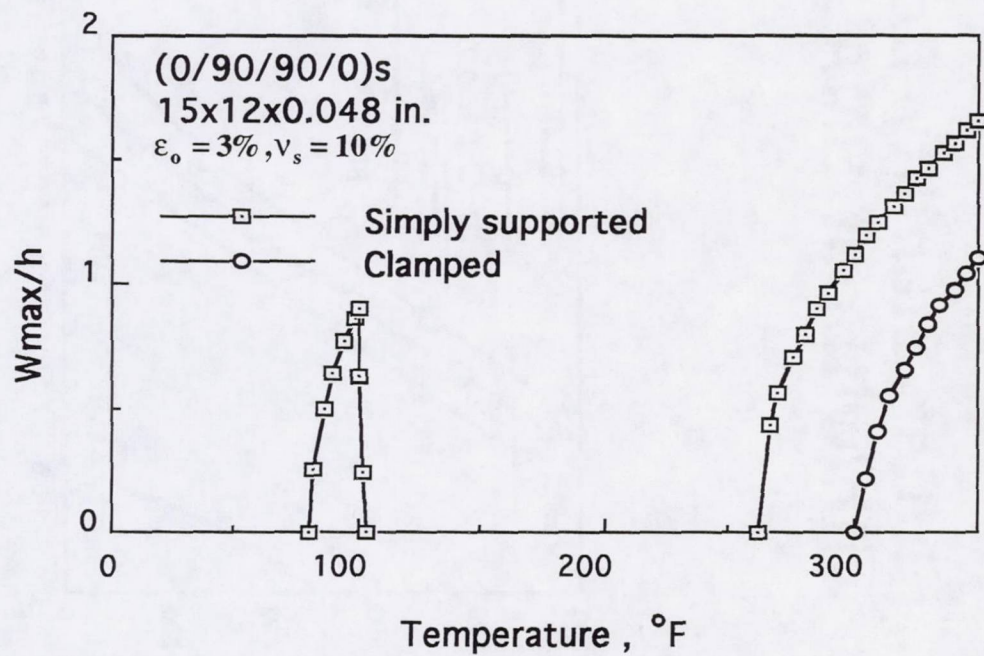
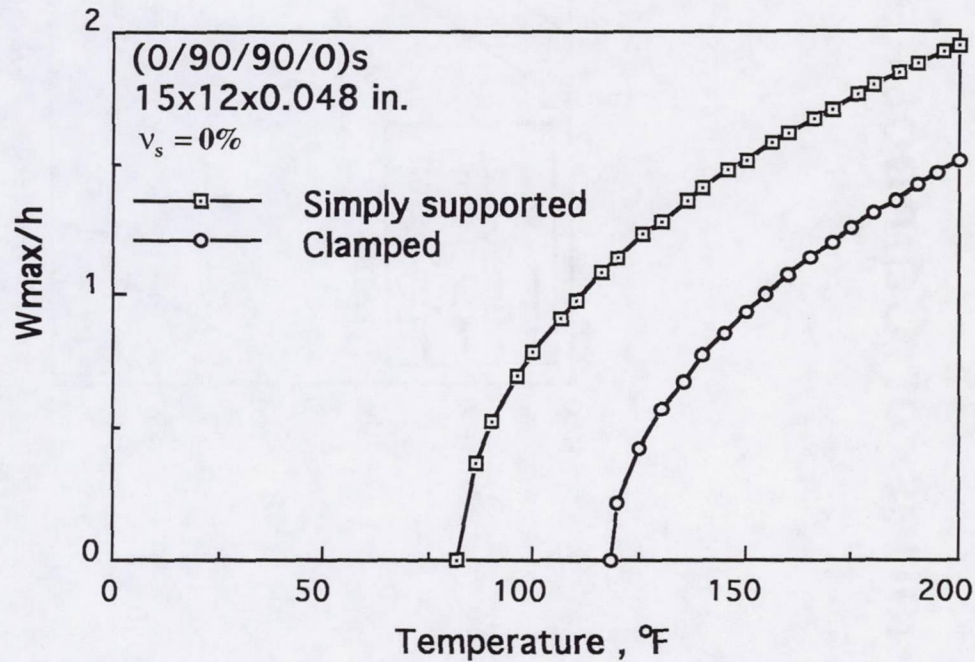
By embedding SMA in composite panel, the panel becomes much stiffer at elevated temperatures. That is because the large tensile inplane forces induced in the panel from the SMA recovery stress. A stiffer panel would certainly yield smaller dynamic responses.

Panel flutter has been encountered in the operation of aircraft and missiles at supersonic speed. It has been concluded that the temperature induced compressive thermal stresses will reduce the critical flutter dynamic pressure (lower aircraft speed limit). Slide 2 shows the nondimensional critical flutter dynamic pressure versus temperature for a simply supported square panel with/without SMA fibers. The aerodynamic theory used at supersonic speeds is the quasisteady first-order piston theory aerodynamics. Results show that the flutter stability region is enlarged significantly at high temperatures with the increase of SMA fiber volume fraction and initial strain. And the SMA fiber volume fraction is more effective than the initial strain in panel flutter control.

Acoustic fatigue has been as one of the critical considerations in the design and development of high speed flight vehicles. The HSCT will subject the skin panels to significant acoustic (fluctuating boundary layer or jet noise) and thermal loads. Slide 3 shows the total maximum panel deflection, maximum thermal postbuckling deflection and RMS maximum deflection, at 300°F and 100 dB sound spectrum level. It shows that significant reductions in acoustic random response can be realized using SMA embedded in composite panels.

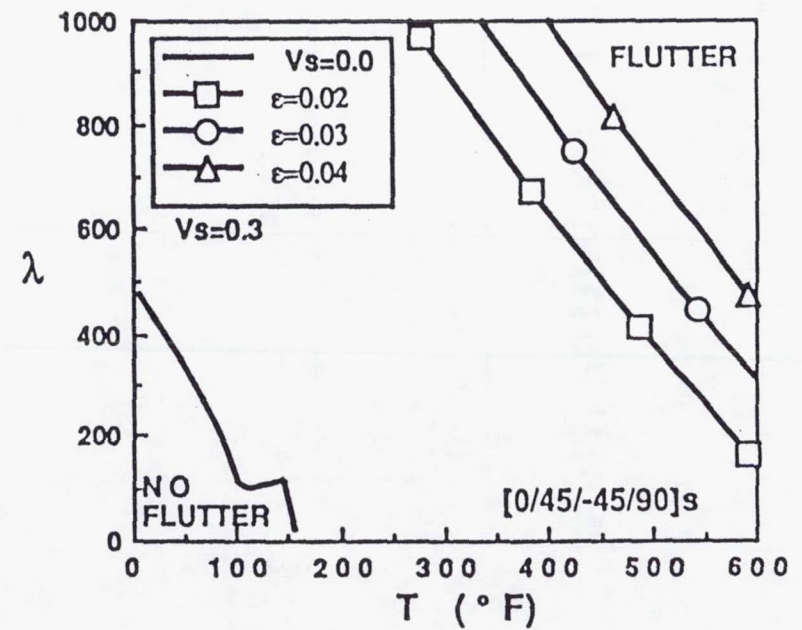
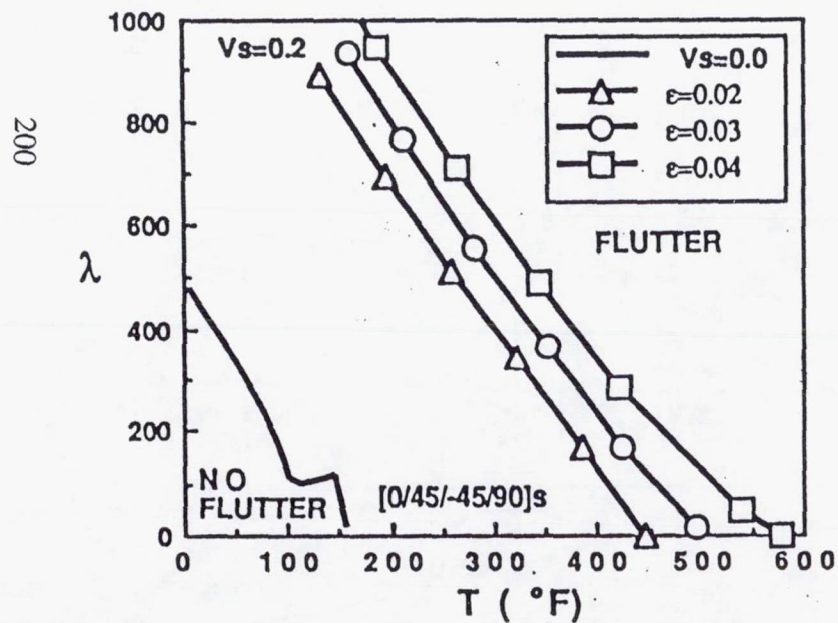
RESULTS

● Thermal Postbuckling Deflections



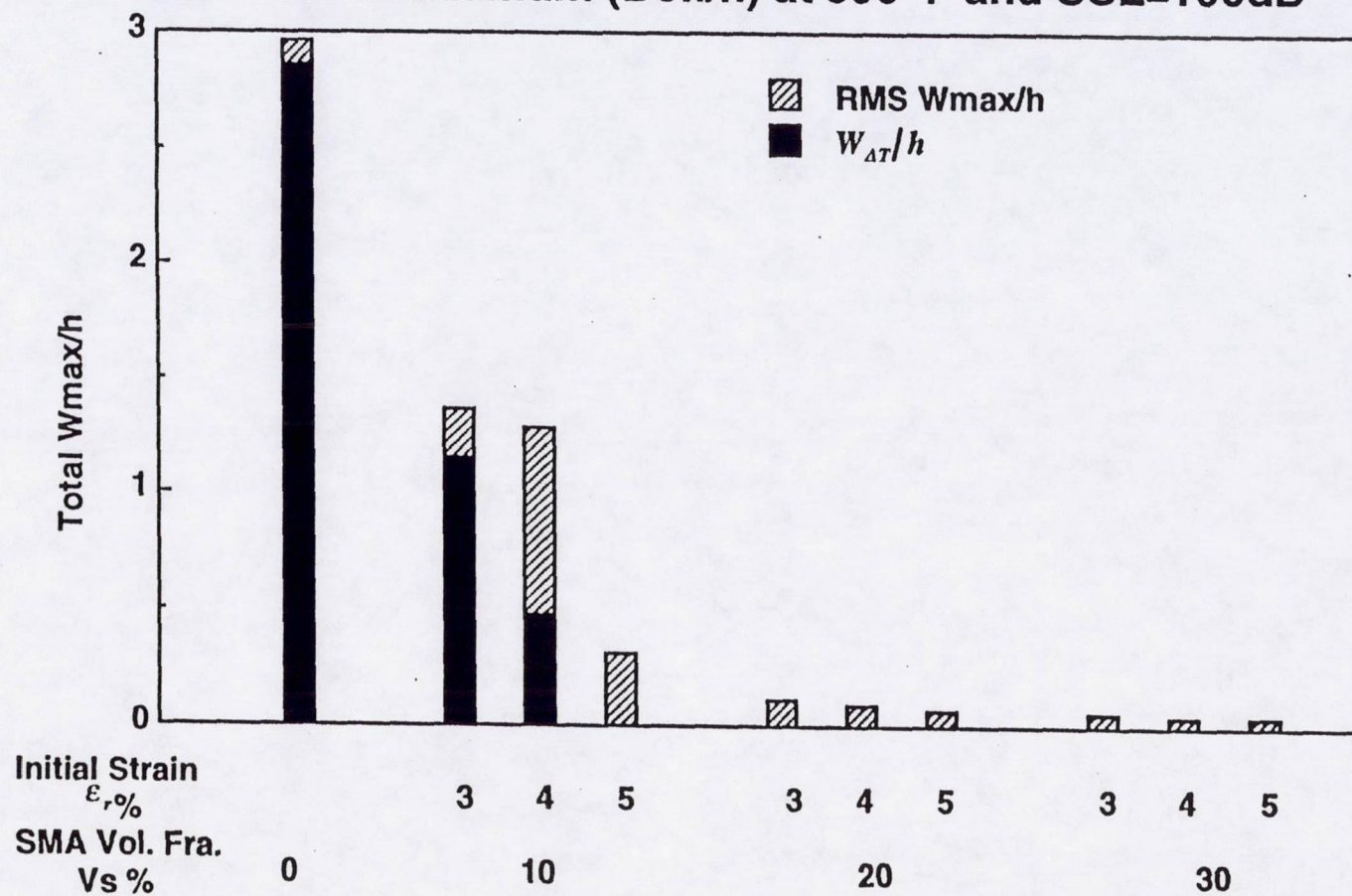
RESULTS

Flutter Stability Boundaries of Composite Plates with/without SMA



RESULTS

Total Maximum (Def./h) at 300 °F and SSL=100dB



Page intentionally left blank

57-05
61428
235093

Active and Passive Damping of Vibration for Rotorcraft Applications

Norman M. Wereley, G. M. Kamath, and C. Smith
Center for Rotorcraft Education and Research University of Maryland
College Park, MD 20742

4 P.

The Smart Structures University Research Initiative at University of Maryland is developing smart rotor technology and analysis methods to be applied towards the mitigation of vibration, stability augmentation, and acoustics. Over 16 faculty are teamed in both helicopter application specific research, as well as generic technology development.

One research thrust focused on helicopters is the development of blade mounted actuators using smart materials such as piezo-electric and magnetostrictive materials using strategies including controllable blade twist and actuation of a trailing edge flap.

A second research thrust focuses on stability augmentation of advanced rotors. We are developing hybrid passive /active damping and vibration control strategies in the development of smart composites. These composites involve sandwiches of polymer composite and visco-elastic material, for both structural and acoustic applications. The visco-elastic material can be used for passive broadband vibration damping in a constrained layer damping strategy. Piezo-actuators, either surface mounted or embedded, are used for the active control of structure-borne noise, as well as for active damping via active shearing of the visco-elastic layer in an active constrained layer damping approach. Point damping applications using electrorheological and magnetorheological fluids are investigated for application to lag mode damping. The applications discussed included lag mode stability augmentation for rotorcraft flexbeams in hingeless/bearingless rotors and interior acoustics control in the helicopter fuselage.

Viscoelastic Damping Techniques for Composite Rotorcraft Flexbeams

The objective of this project is to develop methods of reducing vibration and increasing stability of new composite rotor systems through the use of integral viscoelastic layers.

To understand the mechanisms affecting structural damping of composite I-beams with integral damping layers, an experimental program was initiated. Dynamic testing of Gr/Ep I-beams was conducted in the vacuum chamber. The goals of this testing included characterization of modal damping and frequency properties. To accomplish this, the beams were mounted in a simulated rotor hub and excited in flap using two piezo crystals mounted at the root of the beam. The first natural frequency of the beam was determined using a swept sine input sent to the piezos and data collected from a full strain gage bridge near the root of the beam. Both the piezo input and the strain gage output were collected, and the transfer function was estimated at each rotational speed of interest. For each rotational speed, the beam was then excited sinusoidally at its natural frequency. This excitation was abruptly stopped

and the resulting transient data collected. The moving block algorithm was then used to estimate damping ratios.

As expected, the natural frequency results (Figure 1) exhibit a well behaved increase in frequency corresponding to an increase in rotational speed. Figure 2 shows that in the non-rotating case, there was approximately a 100% increase in damping ratio for a 26.2% volume fraction of viscoelastic, while at 750 RPM, the centrifugal forces reduced the effectiveness to about a 60% increase. The centrifugal loading also produced an overall net reduction in the damping ratio in all cases.

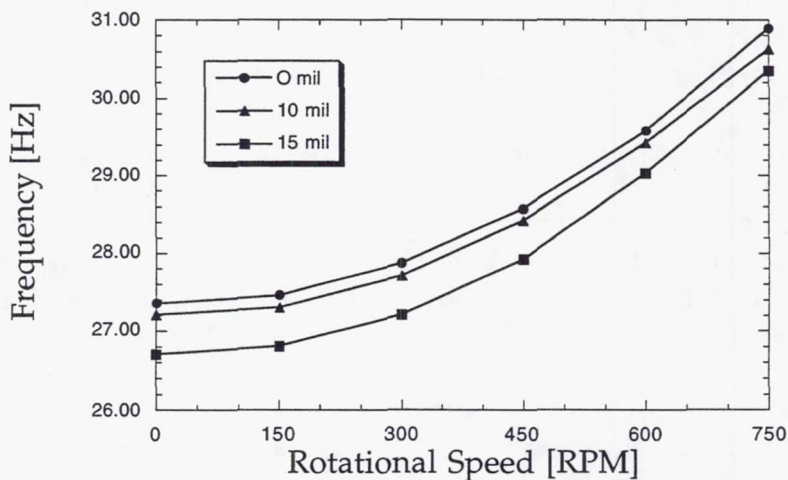


Figure 1. Frequency Data

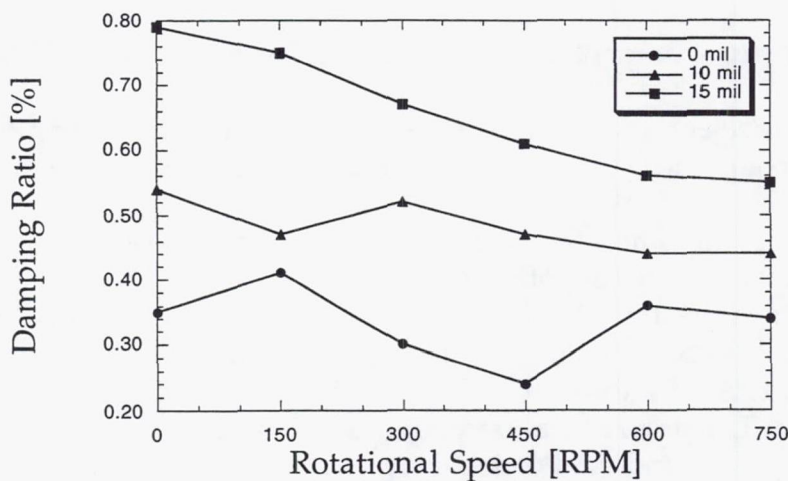


Figure 2. Damping Ratio Results

Nonlinear Viscoelastic-Plastic Model for Electro-rheological Fluids

Electro-rheological (ER) fluids are colloidal suspensions that exhibit dramatic reversible changes in properties when acted upon by an electric field. ER fluids are being used in a wide range of devices such as dampers, brakes, clutches, valves and engine mounts. Thus the need to understand the complex nonlinear behavior of ER fluids is a strong motivation. Once the viscoelastic material behavior of these materials is well characterized, application of these materials in lag mode dampers can proceed.

ER fluids have two distinct rheological domains: the pre-yield and the post-yield domains. In the pre-yield domain, the material behaves like a viscoelastic solid and in the post-yield domain the material behaves like a viscous fluid. The yield stress value has a quadratic dependence on the electric field. The model proposed here combines the above two dominant characteristics denoted by linear operators L_1 and L_2 . The nonlinear behavior is incorporated into the model using strain rate dependent functions, S_1 and S_2 via a network shown in Fig. 3. A sinusoidal strain input is assumed and the stress response calculated. The model parameters are determined by using Least Mean Square estimation technique to minimize the error between the stress values calculated using the model and the stress values measured from experiments. Even a highly nonlinear response similar to that of a Bingham plastic material can be accurately simulated using this model as shown in Fig. 4. A simple network based approach is used to incorporate the effects of strain amplitude and excitation frequency on the ER material behavior.

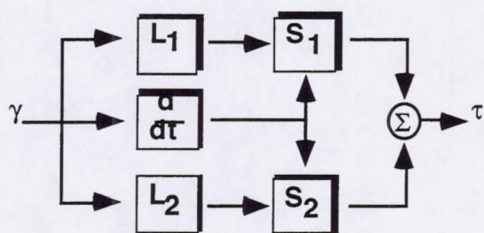


Figure 3. Single frequency network

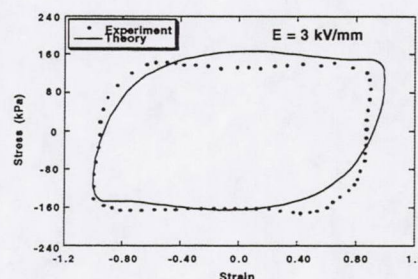


Figure 4. Hysteresis loop

Conclusion

Advanced helicopter rotor systems, such as those proposed for military rotorcraft in the near future, are mechanically less complex than traditional rotor systems. This simplification may lead to problems with both air and ground resonance. Damping can be a major stabilizing influence for these conditions, and a method of introducing damping in the flexbeam would allow for greater aeromechanical stability. Distributed and point damping strategies are currently being investigated to this end.

Page intentionally left blank

58-71
61432
235094
4P.

Active Control of Noise Using Actuator/Sensor Arrays

Douglas K. Lindner and Patrice Winder
Bradley Department of Electrical Engineering
Virginia Tech
Blacksburg, VA 26061-0111, USA

and

George Kirby
Code 6380
Naval Research Laboratory
Washington, DC 20375-5000, USA

Current research in smart structures is directed toward the integration of many actuators and sensors into a material. In this paper we investigate the possibility of using this instrumentation for active noise control from a vibrating structure. Current technology for reducing radiated sound is limited by the instrumentation for the control system. These control systems employ relatively small numbers of sensors and actuators. Hence, these control systems must rely on a model of the structure to estimate and control the global vibrations that contribute to the far field pressure. For complex, realistic structures the development of such a model is a formidable task. The model is a limiting factor in the continuing development of structural acoustics.

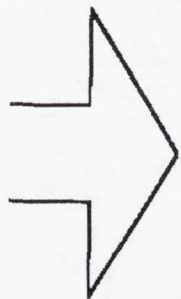
In this paper we propose to increase the number of actuators and sensors of a smart material to offset the complexity of the model used for control design. The sensor arrays will be used to directly sense the shape of the structure rather than using a model of the structure to indirectly sense the shape of the structure. The actuator array is used to apply distributed forces to the structure, rather than using the structure itself as a load path. A control system for the active cancellation of sound is derived from standard control system methodologies.

Instrumentation: Smart Material

Arrays of Actuators and Sensors

**Many Actuators and Sensors
per Modeshape Wavelength**

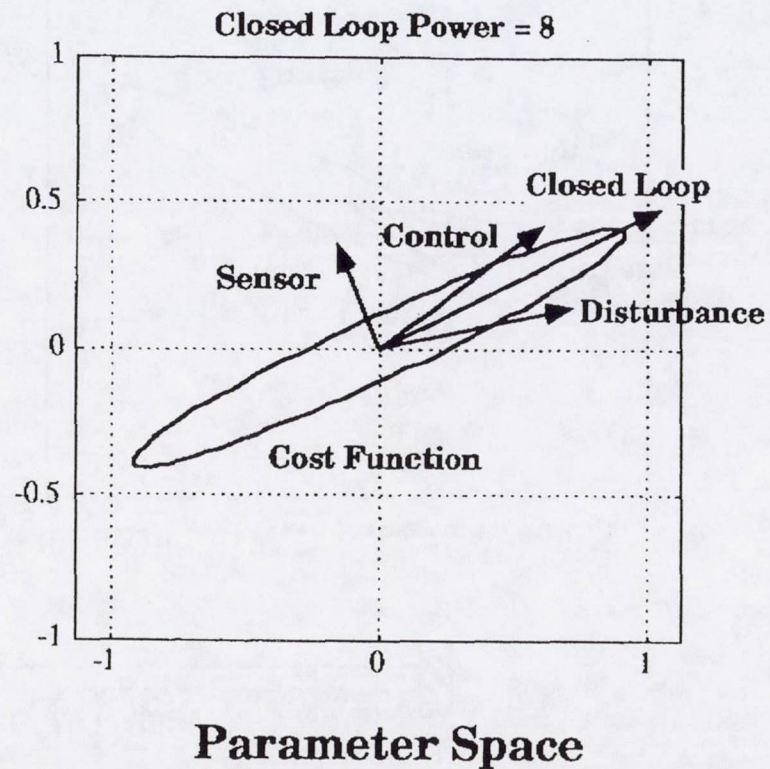
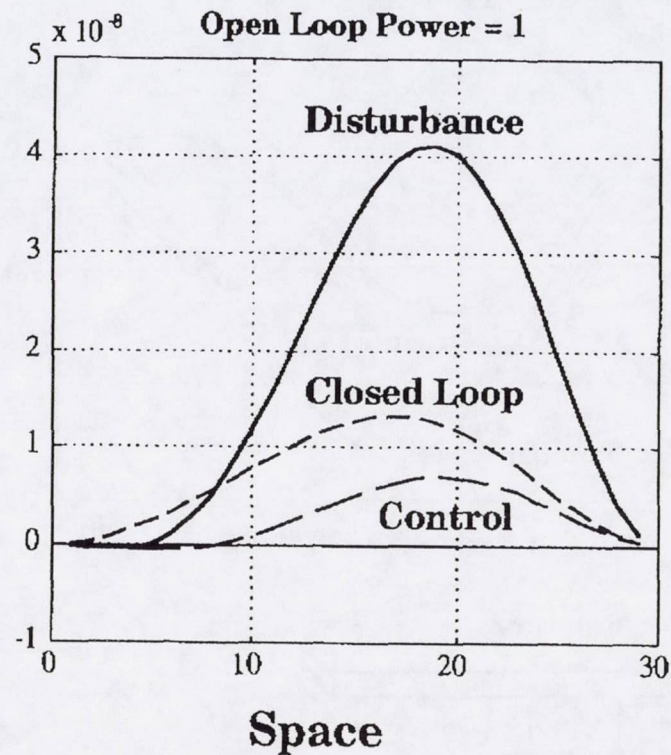
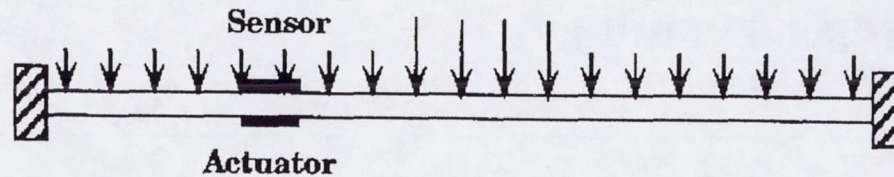
Many More Actuators and Sensors Than Modes



New Class of Control Systems?

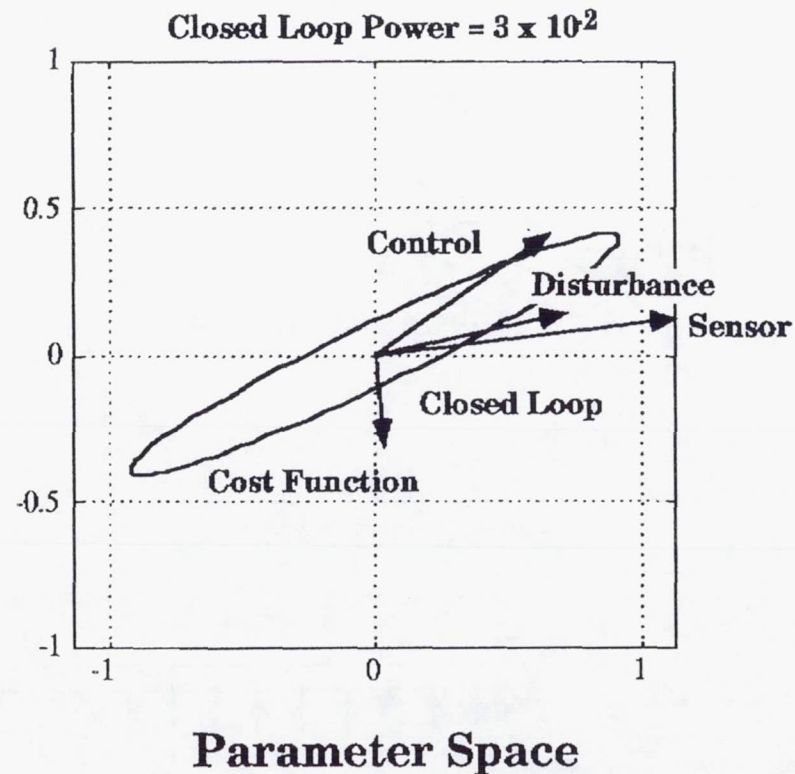
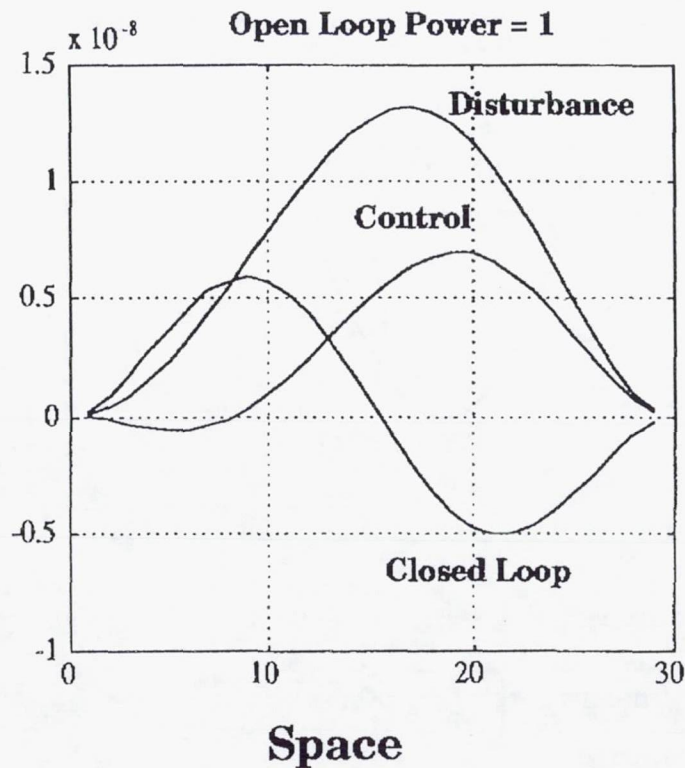
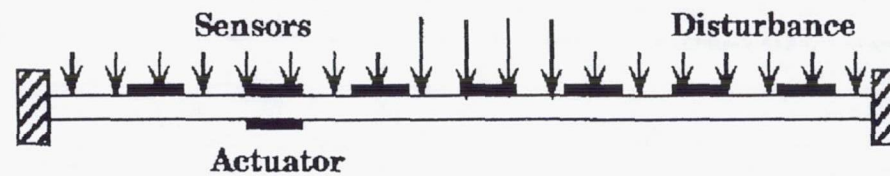
The Bradley Department of Electrical Engineering

Example: Point Actuators and Sensors



The Bradley Department of Electrical Engineering

Example: Point Actuator and Distributed Sensors



59-71
61434
235095
4p.

Aircraft Interior Noise Control Using Distributed Piezoelectric Actuators

Jian Q. Sun
Department of Mechanical Engineering
University of Delaware
Newark, DE 19716, USA

Structural controls have been used to reduce acoustic radiation from vibrating structures. It is well known that in some cases, a structural control system can reduce the noise and, at the same time, increase the structural vibration. This is one of the concerns with the structural control approach for solving the noise problem. Developing a control system that can reduce the noise and structural vibration at the same time is an important task. This talk presents one of possible technical approaches for accomplishing this task. The target application of the research is for aircraft interior noise control.

The emphasis of the present approach is not on control strategies, but rather on the design of actuators for the control system. In the talk, a theory of distributed piezoelectric actuators is introduced. A uniform cylindrical shell is taken as a simplified model of fuselage structures to illustrate the effectiveness of the design theory. The actuators developed are such that they can reduce the tonal structural vibration and interior noise in a wide range of frequencies. Extensive computer simulations have been done to study various aspects of the design theory. Experiments have also been conducted and the test results strongly support the theoretical development.

A Dilemma

- **Structural control is a very effective means to reduce acoustic radiation due to structural vibration.**
- **However, a structural control system sometimes reduces noise radiation at the price of increasing the structural vibration.**

Motivations/Objectives

Solutions to the Dilemma

- **Control Strategy - Cost Function = Noise + Vibration**
 - Less optimal noise reduction
 - Increased number of channels
- **Distributed Actuators - The Present Approach**
 - + Inherent ability to control vibration and noise at the same time
 - + Optimal noise reduction without adding more channels

Motivations/Objectives

Design Theory of Optimal Actuators For Interior Noise Control

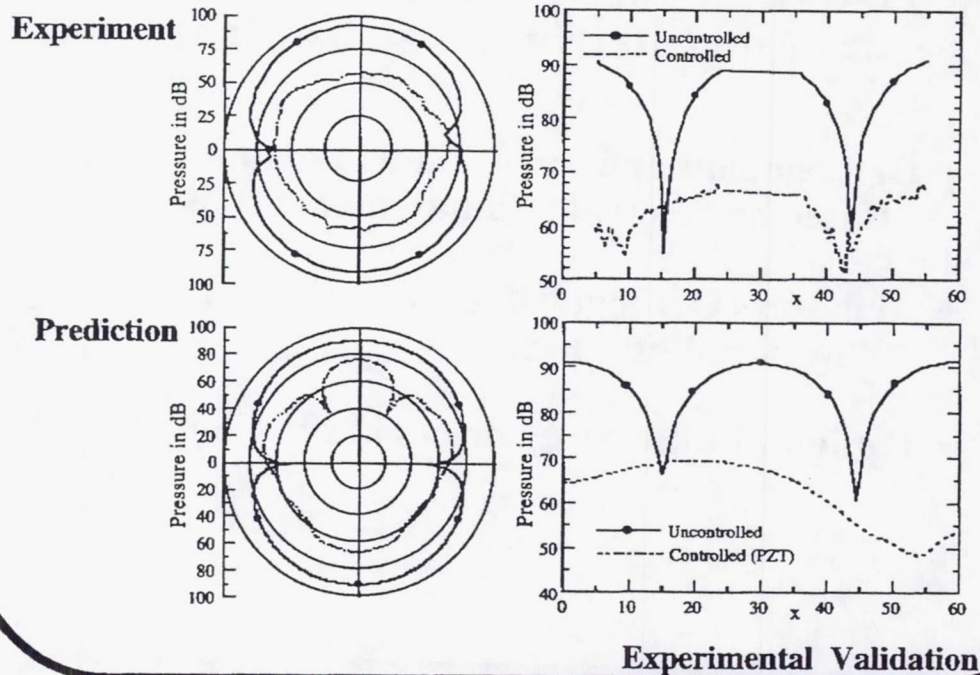
- **Orthogonal Partition of the Wavenumber Space
Based on Acoustic Radiation Analysis**
- **Actuators Orthogonal to Each Other in the
Wavenumber Space**
- **Optimal Influence Matrices of the Control System**

Piezoelectric Actuator Model

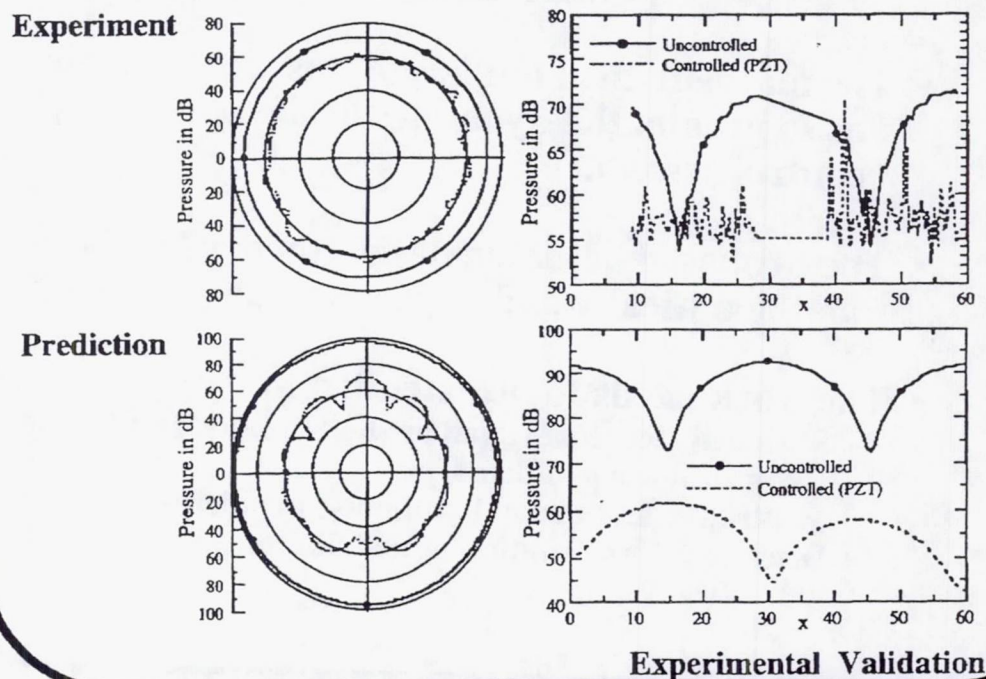
Conclusions

- **The mathematical models of this work enable
us to predict the dynamics of the noise
control system.**
- **The proposed actuator design theory has been
mathematically and experimentally verified.**
- **The work needs to be extended to**
 - + **Stiffened structures such as shells, plates and beams**
 - + **Exterior noise problems**
 - + **Multi-tone and broad band noise problems**
 - + **Discrete approximation of distributed actuators**

Interior Pressure Distributions (398Hz)



Interior Pressure Distributions (226Hz)



NOISE REDUCTION IN AN AIRCRAFT FUSELAGE MODEL USING ACTIVE TRIM PANELS

Karen H. Lyle, *US Army Vehicle Structures Directorate, Hampton, VA*

Richard J. Silcox, *NASA Langley Research Center, Hampton, VA*

An experiment was conducted to evaluate the use of force actuators on a model aircraft interior trim panel as the control element for active control of interior noise. These experiments were conducted on a composite model of a commuter class aircraft with a floor installed, see the first figure. The trim panel, designed specifically for this study, was constructed in three large identical sections and hard mounted to the ring frames of the primary structure. Piezoceramic actuators were bonded to the outer surface of the trim panels. Studies of the interior pressure response due to both the primary source alone and control sources alone were conducted as well as the control cases.

The trim panel has a 0.25 in. thick honeycomb core with 0.025 in. laminated composite face sheets on either side. These panels have approximately twice the stiffness and thus twice the weight of standard aircraft interior trim panels. The increased stiffness was needed for effective coupling between the trim panel and piezoceramic actuators. A single acoustic loudspeaker, centered at the axial midpoint, generated the acoustic field to be controlled. The control actuators were located in two cross-sections on the center trim panel, 15 inches on either side of the center cross-section.

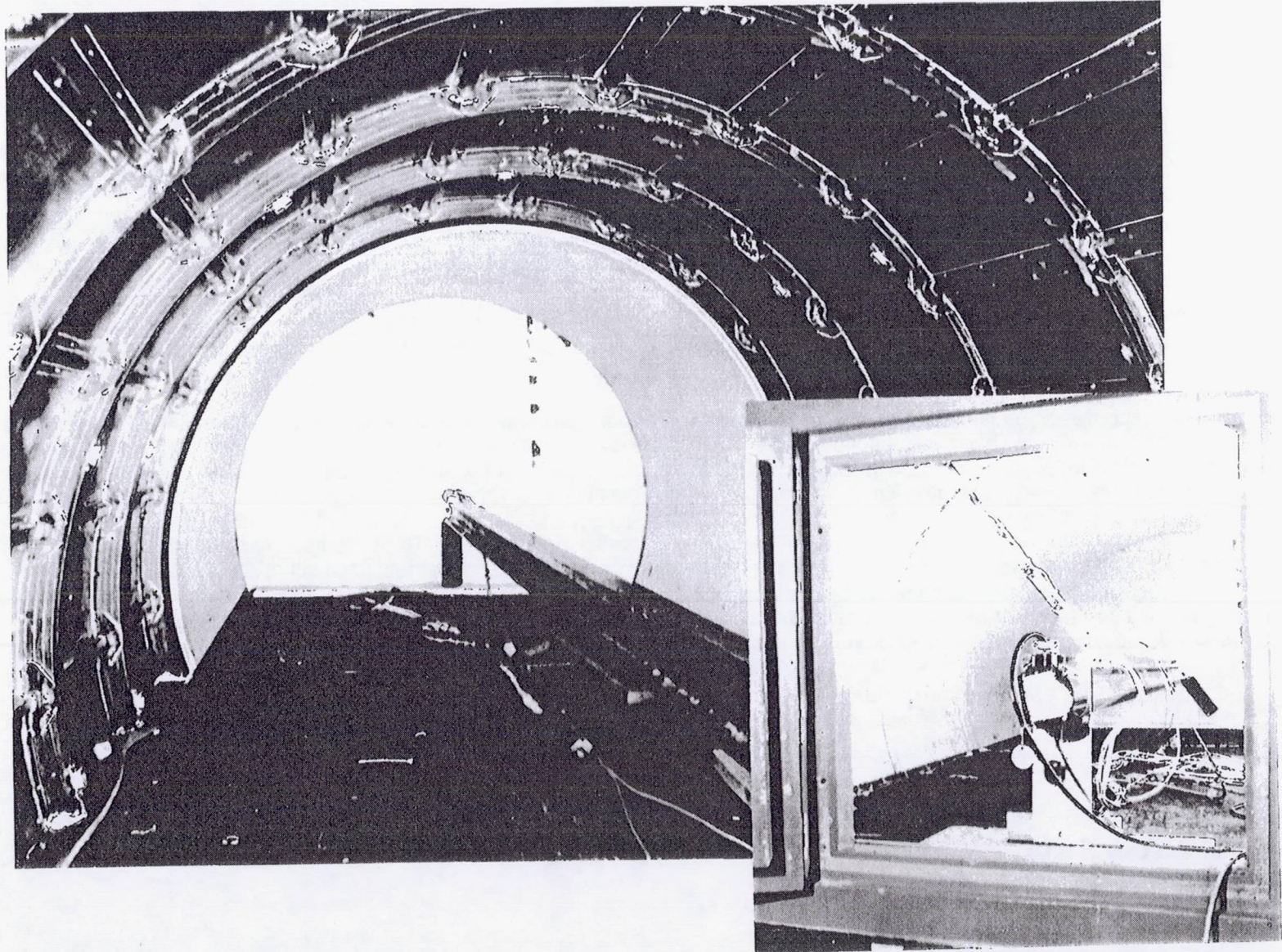
The results for 210 Hz are shown in the second figure. For this particular configuration, two actuator and six error microphone locations were used. The SPL distributions at the center cross-section, P , are given at the bottom of the figure. The average SPL with the controller off is 66.2 dB. Once the controller is turned on, the average cross-section SPL is reduced by 4.7 dB to 61.5 dB. The average SPL reduction for the entire cylinder was 5.1 dB. Modal decompositions of the data show that the amplitude of the dominant acoustic mode was reduced by 23 dB; however, control was limited by residual modes in the cavity that were not controlled by the two actuator control configuration.

Unfortunately, the control at other frequencies was not as good. For example, at 305 Hz, see the third figure, where the interior pressure response due to the external acoustic source was dominated by a different acoustic mode than the interior pressure response driven by the piezoceramic actuators. At this frequency, a controller was implemented with 4 piezoceramic actuator locations and 6 error microphones. The averaged SPL at cross-section, P , was 72.4 dB for no control and 70.2 dB with the controller on. The averaged SPL reduction for the cylinder was only 1.2 dB. The lack of control was attributed to the different coupling between the interior acoustic space and the two types of sources (external acoustic speaker and piezoceramic actuators). This difference in coupling is in strong contrast to previous results attained for control actuators bonded directly to the primary structure.

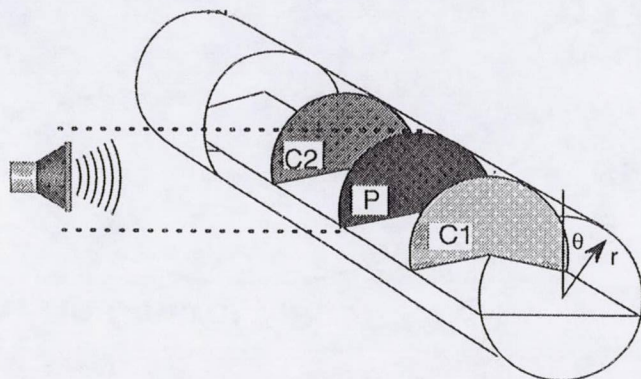
In summary, initial results provided 5 dB global reductions in SPL using active control for some cases. However, for other cases, the lack of control was attributed to strong mismatches between the interior response driven by the exterior acoustic source and that driven by the control sources. Further work is planned to improve the reduction of the interior noise. This will include: adding actuators to the remaining trim panels; utilizing control algorithms that will group actuators; and vibration isolating the trim panel from the primary structure.

510-71
61436
235096
410.

INTERIOR OF FUSELAGE MODEL



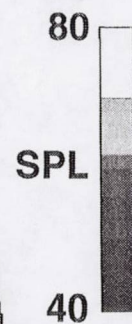
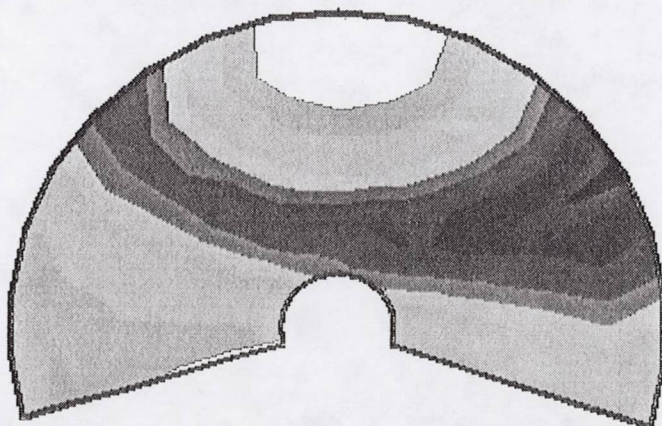
EFFECT OF CONTROL AT 210 HZ



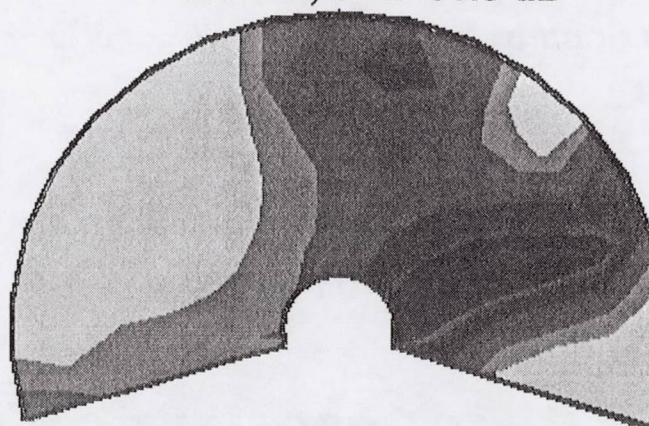
Control Configuration
2 Pairs piezoceramic actuators
6 Error microphones

Average SPL Reduction = 5.1 dB

No Control, SPL=66.2 dB

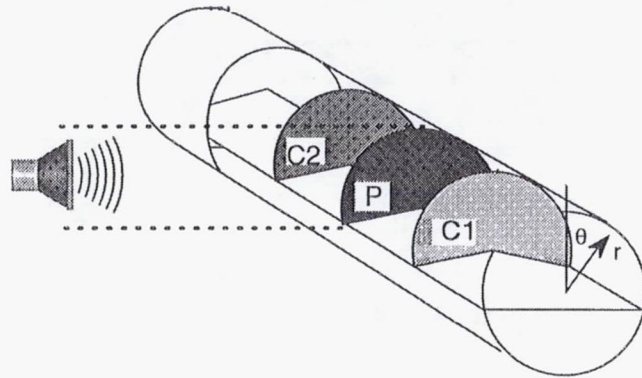


Control, SPL=61.5 dB



EFFECT OF CONTROL AT 305 HZ

Using 4 Actuators



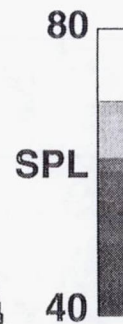
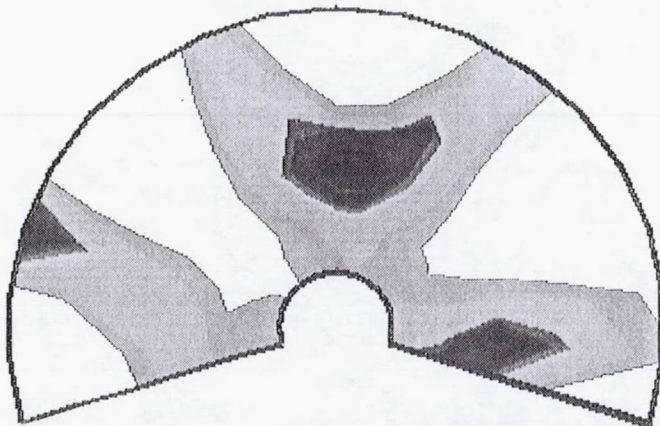
Control Configuration

4 Pairs piezoceramic actuators

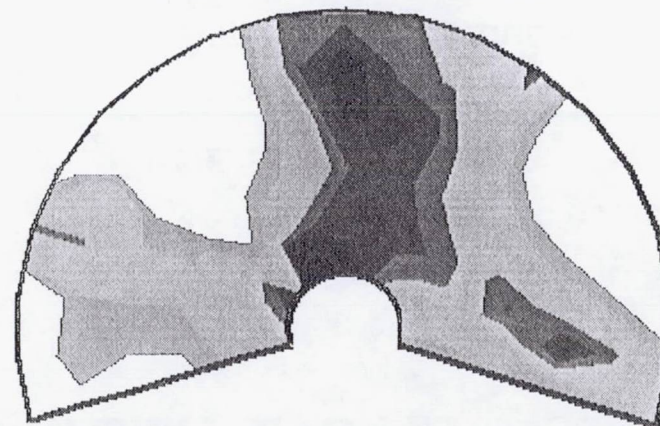
6 Error microphones

Average SPL Reduction = 1.2 dB

No Control, SPL= 72.4 dB



Control, SPL= 70.4 dB



STRUCTURAL ACOUSTIC RESPONSE OF SHAPE MEMORY ALLOY HYBRID COMPOSITE PANELS

Travis L. Turner
Structural Acoustics Branch
NASA Langley Research Center
Hampton, VA 23681-0001

511-39
61438
235097
y/p.

Abstract

A method has been developed to predict the structural acoustic response of shape memory alloy hybrid composite panels subjected to acoustic excitation. The panel is modeled by a finite element analysis and the radiated field is predicted using Rayleigh's integral. Transmission loss predictions for the case of an aluminum panel excited by a harmonic acoustic pressure are shown to compare very well with a classical analysis. Predictions of the normal velocity response and transmitted acoustic pressure for a clamped aluminum panel show excellent agreement with experimental measurements. Predicted transmission loss performance for a composite panel with and without shape memory alloy reinforcement are also presented. The preliminary results demonstrate that the transmission loss can be significantly increased with shape memory alloy reinforcement.

Introduction

Interior noise and sonic fatigue are important issues in the development and design of advanced subsonic and supersonic aircraft. Conventional aircraft typically employ passive treatments, such as constrained layer damping and acoustic absorption materials, to reduce the structural response and resulting acoustic levels in the aircraft interior. These techniques require significant addition of mass and only attenuate relatively high frequency noise transmitted through the fuselage. Recent work has been aimed at developing adaptive and/or active methods of controlling the structural acoustic response of panels to reduce the transmitted noise¹. A finite element formulation was recently developed to study the dynamic response of shape memory alloy (SMA) hybrid composite panels (conventional composite panel with embedded SMA fibers) subject to combined acoustic and thermal loads². Further analysis has been performed to predict the far-field acoustic radiation using the finite element dynamic panel response prediction³.

Computational Method

The panel vibration response and acoustic radiation predictions presented in this paper were generated using a previously developed computational method. The panel was modeled using a finite element analysis and the radiated acoustic field was predicted using Rayleigh's integral. The approach can easily include effects such as SMA fiber reinforcement, static large deflection thermal post-buckling, non-symmetric SMA distribution or lamination, and obliquely incident acoustic excitation of arbitrary temporal nature. Details of the mechanical model for the SMA (Nitinol) hybrid composites, the finite element formulation, and the response analysis approach can be found in references 2 and 3.

Experimental Setup and Procedure

Experiments were conducted in the Transmission Loss Apparatus at NASA Langley Research Center to provide baseline measurements of the vibration response and acoustic radiation of an isotropic panel subject to acoustic loading. The apparatus consists of a source room and a receiving room separated by a massive partition. A flat clamped aluminum panel ($0.3048 \times 0.1778 \times$

1.016×10^{-3} m) was installed in a baffle mounted in the partition. Normal incidence acoustic excitation was provided by a speaker positioned approximately 0.9144 m from the panel. The source acoustic pressure was measured in the plane of the panel using one 12.7×10^{-3} m microphone with the panel removed from the baffle. The transmitted acoustic pressure was measured using a single vertical microphone array consisting of three 12.7×10^{-3} m microphones; one at the height of the panel center, one 0.3048 m above the center mic, and one 0.3048 m below the center mic. The panel vibration response was measured with a scanning laser vibrometer. Details of the experimental setup and procedure can be found in reference 4.

Results and Discussion

The predicted results presented in this paper were generated using material properties for aluminum, graphite-epoxy, and Nitinol from reference 3. Results for two isotropic panels and two composite panels are presented in the following discussions.

A simply supported aluminum panel ($0.381 \times 0.1524 \times 0.8128 \times 10^{-3}$ m) was analyzed with the present computational method for comparison to analytical results presented by Roussos⁵. A comparison of the transmission loss (TL) predicted using each method for an incident plane wave at $\theta_i = 60^\circ$ and $\phi_i = 0^\circ$ is shown in figure 1. It can be seen that the present method agrees very well with the classical approach.

Comparisons of the predicted and measured panel normal velocity and transmitted pressure PSDs for a clamped aluminum panel ($0.3048 \times 0.1778 \times 1.016 \times 10^{-3}$ m) are shown in figures 2 and 3. Comparisons of the predicted and measured panel normal velocity are shown in figure 2 for two measurement locations. The agreement is excellent with the exception of the appearance of additional peaks in the measured spectra. These peaks are attributable to the first and second non-symmetric modes of the panel. The acoustic excitation generated by the speaker, although fairly uniform in magnitude, apparently was sufficiently oblique to excite the non-symmetric modes. It was assumed in the analysis that the incident pressure was uniform and normal. Thus, the non-symmetric modes do not appear in the predictions.

Comparisons of the predicted and measured transmitted pressure are shown in figure 3 for two measurement locations. It can be seen that the agreement is very good, particularly near the panel fundamental frequency. Theoretically, the pressure at the top and bottom microphones of the array should be the same, due to symmetry. However, the measured spectra showed an increase in the levels between the peaks with decreasing distance to the hard room floor. Thus, some of the discrepancies are attributable to receiving room reflections. Also note that the non-symmetric modes do not radiate, as expected.

Finally, transmission loss curves were generated for simply supported (0,45,-45,90)_s composite panels ($0.381 \times 0.1524 \times 0.8128 \times 10^{-3}$ m) with and without shape memory alloy wire reinforcement. The transmission loss as a function of harmonic excitation frequency is shown in figure 4 for two panels at ambient temperature (21.1°C); a graphite-epoxy panel without SMA reinforcement, and a hybrid graphite-epoxy panel with 10% SMA volume fraction and 5% initial strain in all layers (SMA inactivated). The shift in the first transmission loss dip at the fundamental frequency, and the moderate TL increase for most of the frequency range above the fundamental frequency, is attributable to the increased mass of the SMA reinforced panel.

The transmission loss for the same hybrid composite panel at 65.6°C and 148.9°C (i.e., SMA activated) is shown in comparison to the panel with inactive SMA in figure 5. It can be seen that at the elevated temperatures the increased stiffness due to tensile inplane recovery forces has greatly increased the fundamental frequency, and thus the fundamental-frequency TL dip. Consequently, there is a significant increase in the transmission loss at low frequencies (below 100 Hz). However,

at higher frequencies the TL is nearly unchanged. This is due to the fact that the TL is mass controlled at high frequencies. The reduction in the low frequency TL for the hybrid panel at 148.9°C, relative to that for the 65.6°C panel, is caused by counteracting compressive inplane forces from thermal expansion effects. Improved performance may be achievable by optimizing the SMA reinforcement for maximum frequency shift, added damping, or modification of modal radiation efficiencies.

Conclusions

A method has been developed to predict the structural acoustic response of shape memory alloy hybrid composite panels subjected to thermal and acoustic loads. The panel was modeled by a finite element analysis and the radiated field was predicted using Rayleigh's integral.

Analytical results were generated for an aluminum panel subject to harmonic acoustic excitation and compared with a classical analysis for validation of the approach. The two methods agreed very well.

Baseline experimental measurements of the velocity response and acoustic radiation of an aluminum panel due to normally incident random acoustic excitation have been acquired. Comparisons of the predicted and measured power spectral densities of the panel normal velocity and transmitted acoustic pressure show excellent agreement.

Transmission loss predictions were presented for graphite-epoxy panels with and without shape memory alloy fiber reinforcement. It was found that the main effect of shape memory alloy reinforcement on the transmitted acoustic power is a shift in the first transmission loss dip, due to a shift in the panel fundamental frequency. It was observed that further improvements in the panel transmission loss could be realized with more effective use of the SMA reinforcement to maximize the fundamental frequency shift, increase damping, and reduce the radiation efficiency of the fundamental mode.

References

1. Fuller, C. R.; Rogers, C. A.; and Robertshaw, H. H.: "Control of Sound Radiation with Active/Adaptive Structures," *Journal of Sound and Vibration*(1992) **157**(1), 19-39.
2. Turner, T. L.; Zhong, Z. W.; and Mei, C.: "Finite Element Analysis of the Random Response Suppression of Composite Panels at Elevated Temperatures Using Shape Memory Alloy Fibers," AIAA Paper No. 94-1324-CP, *Proceedings of the 35th Structures, Structural Dynamics, and Materials Conference*, Hilton Head, SC, April 18-21, 1994, pp. 136-146.
3. Turner, T. L.; Singh, M. P.; and Mei, C.: "A Spectral Analysis Approach for Acoustic Radiation from Composite Panels," AIAA Paper No. 95-1303-CP, *Proceedings of the 36th Structures, Structural Dynamics, and Materials Conference*, New Orleans, LA, April 10-13, 1995, pp. 1262-1271.
4. Turner, T. L.; and Rizzi, S. A.: "Prediction and Measurement of the Vibration and Acoustic Radiation of Panels Subjected to Acoustic Loading," INCE Paper No. 95-91, *Proceedings of the 1995 International Congress on Noise Control Engineering*, Newport Beach, CA, July 10-12, 1995, pp. 315-318.
5. Roussos, L. A.: "Noise Transmission Loss of a Rectangular Plate in an Infinite Baffle," NASA TP-2398, March, 1985.

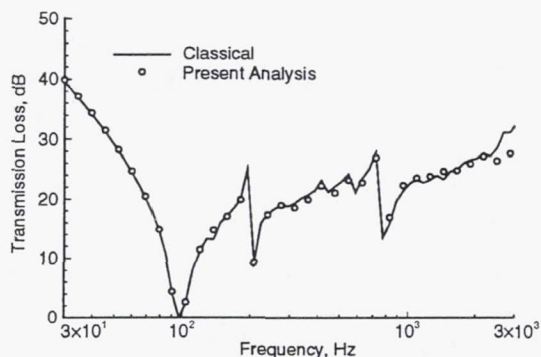


Figure 1: Transmission loss for a $0.381 \times 0.1524 \times 0.8128 \times 10^{-3}$ m aluminum panel with $\theta_i=60^\circ$ and $\phi_i=0^\circ$.

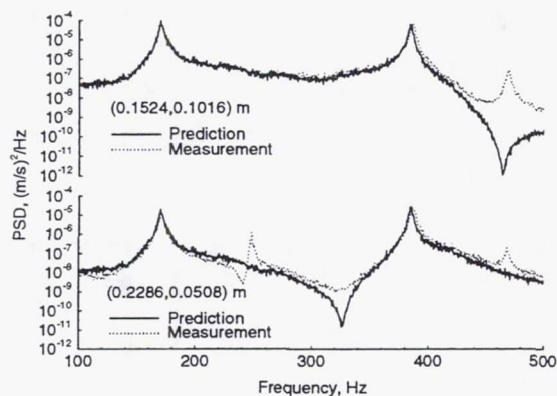


Figure 2: Comparison of predicted and measured panel normal velocity PSD at two locations.

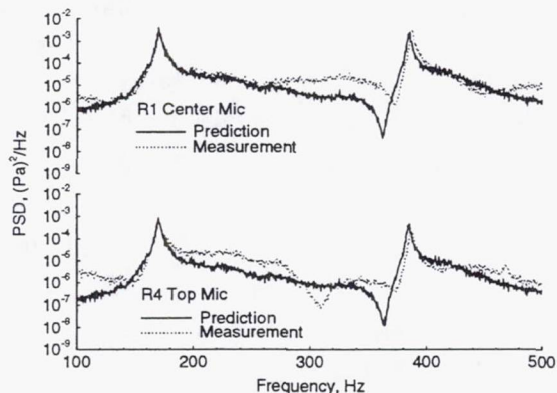


Figure 3: Comparison of the predicted and measured transmitted pressure PSD at two far-field locations.

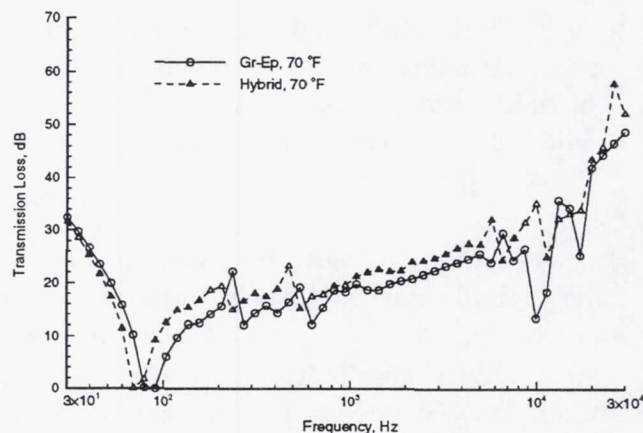


Figure 4: Transmission loss for a $0.381 \times 0.1524 \times 0.8128 \times 10^{-3}$ m $(0/45/-45/90)_s$ composite panel with $\theta_i=60^\circ$ and $\phi_i=0^\circ$.

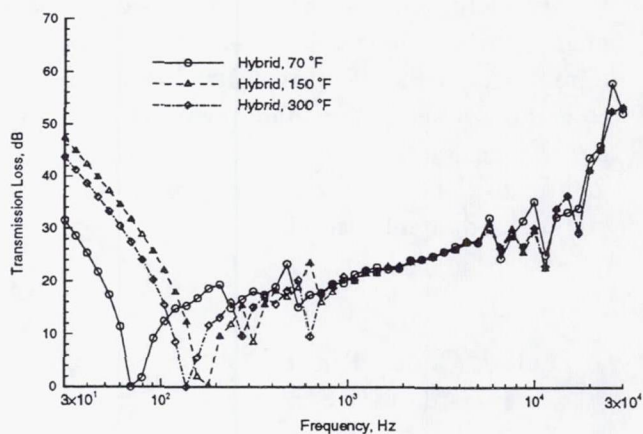


Figure 5: Transmission loss for a $0.381 \times 0.1524 \times 0.8128 \times 10^{-3}$ m $(0/45/-45/90)_s$ composite panel with $\theta_i=60^\circ$ and $\phi_i=0^\circ$.

SPICES and SMS Technology Developments

Chairperson: Dr. Lucas Horta

Page intentionally left blank

5/2-08
ACS 619
61440

**Design, Fabrication, and Calibration of an Embedded Piezoceramic
Actuator for Active Control Applications**

235098

Gary H. Koopmann, George A. Lesieutre, Shoko Yoshikawa, Weicheng Chen,
John B. Fahnlne, Suresh Pai, and Brian Dershem
Center for Acoustics and Vibration, The Pennsylvania State University,
University Park, PA 16902

1 p.

In this presentation, the authors describe the design and fabrication processes for a PZT strain actuator that evolved during the initial stages of a research effort to synthesize and process intelligent, cost effective structures (SPICES). The actuator performance requirements were similar to those of conventional actuators, e.g., it had to be robust, highly efficient with adequate force and stroke, as lightweight as possible, and most importantly, affordable. Further, since the actuator was to be integrated within a composite structure, it had to be compatible with the host material and easily embeddable during the fabrication process. In control applications employing strain devices as actuators, a good bond between this actuator and host material is critical to their successful operation. This criterion is often difficult to achieve when attempting to join ceramics with metals or polymers with dissimilar properties such as Young's moduli, thermal expansion coefficients, etc. One unique feature of the actuator design that evolved in this project is that the need for direct bonding between the PZT ceramic and polymers was circumvented, i.e. the strain transfer to the host material was achieved via a frame surrounding the ceramic. Consequently, the frame material could be selected (or coated) for compatibility with the host material. A second feature is that the frame enclosed a co-fired, multilayered, PZT stack that was used to minimize the voltage requirements while maximizing the output strain.

Page intentionally left blank

SLB-27
61443
235099
8P.

Manufacturing of Smart Structures Using Fiber Placement Manufacturing Processes

Matthew M. Thomas, Robert A. Glowasky, Bruce E. McIlroy, and Todd A. Story
McDonnell Douglas Aerospace
McDonnell Douglas Corporation
P.O. Box 516, St. Louis, MO 63166-0516

ABSTRACT

Smart structures research and development, with the ultimate aim of rapid commercial and military production of these structures, are at the forefront of the Synthesis and Processing of Intelligent Cost-Effective Structures (SPICES) program. As part of this ARPA-sponsored program, MDA-E is using fiber placement processes to manufacture integrated smart structure systems. These systems comprise advanced composite structures with embedded fiber optic sensors, shape memory alloys, piezoelectric actuators, and miniature accelerometers. Cost-effective approaches and solutions to smart material synthesis in the fiber-placement process, based upon integrated product development, are discussed herein.

Keywords: smart structure, composites, manufacturing, fiber-optic sensors, shape memory alloy, piezoelectric actuators.

1. INTRODUCTION

The field of smart structures is characterized by a synergy of research areas, previously considered unrelated, to produce a new generation of structures offering both performance and cost benefits. In recent years, numerous researchers have begun to transition the analytical work that pioneered the interest in smart structures to actual commercial and industrial applications. One of the new areas of research and development generated by this transition was that involving smart structure manufacturing techniques to meet application requirements. In order for these techniques to work for commercial and aerospace applications, they must be cost-effective. An affordable manufacturing process for smart materials can then lend itself to mass production.

The Synthesis and Processing of Intelligent Cost Effective Structures (SPICES) program¹ was funded by the Advanced Research Projects Agency (ARPA) to develop affordable manufacturing processes for smart materials to be used in vibration control. SPICES is a matching funds consortium program, consisting of McDonnell Douglas Aerospace-East and -West (MDA-E and MDA-W), Fiber Materials Incorporated (FMI), General Dynamics' Electric Boat division (GDEB), Martin Marietta Technologies Inc. (MMTI), the Naval Research Laboratories (NRL), Pennsylvania State University (PSU), SRI International, Active Control eXperts (ACX), and United Technologies Research Center (UTRC). SPICES seeks to achieve affordable smart material processing through new, multi-disciplined, integrated product development processes. Developing active elements and composite hosts independently will increase the complexity of integration and limit the potential for cost savings. As such, the SPICES program is geared to examine potentially high payoff manufacturing processes—processes which have synthesized smart materials for eventual military and commercial vibration control applications.

The focus of this effort is to expand solutions to real-world problems associated with the affordable manufacture of practical commercial and industrial smart structures. Since application-driven smart structures combine advanced composite material fabrication techniques with embedding of relatively delicate fiber-optic sensors and piezoelectric (PZT) actuators, manufacturing a smart structure for a specific application requires that an integrated product design and manufacturing process be established. The primary concerns during this integrated process are actuator and sensor survivability during and after fabrication, interfaces between smart devices and host composite material, actuator and sensor lead egress, product reliability, product performance, structural integrity of the host, and actuator and sensor integration into the structure. MDA-E, as part of the SPICES consortium, has addressed these problems and created real world solutions that easily lend themselves to developing affordable manufacturing processes.

Export Authority 22 CFR 125.4(b) (13)

In particular, MDA-E has developed new techniques for embedding and egressing fiber optic sensors and piezoelectric actuators. Specialized manufacturing techniques have been developed, using state-of-the-art fiber placement processing in conjunction with new forms of shape memory alloy (SMA) and PZT actuators produced by MMTI, PSU, and ACX. These techniques have been demonstrated in product manufacturing and are detailed in this paper.

2. FIBER PLACEMENT PROCESS

The selection of a manufacturing process appropriate for most structures depends upon many factors. These factors include production rate, geometric complexity, structural requirements, and material requirements, as Figure 1 illustrates. For the military application portion of the SPICES program, fiber placement of a thermoplastic material (with smart subsystems subsequently embedded) was the manufacturing process selected¹.

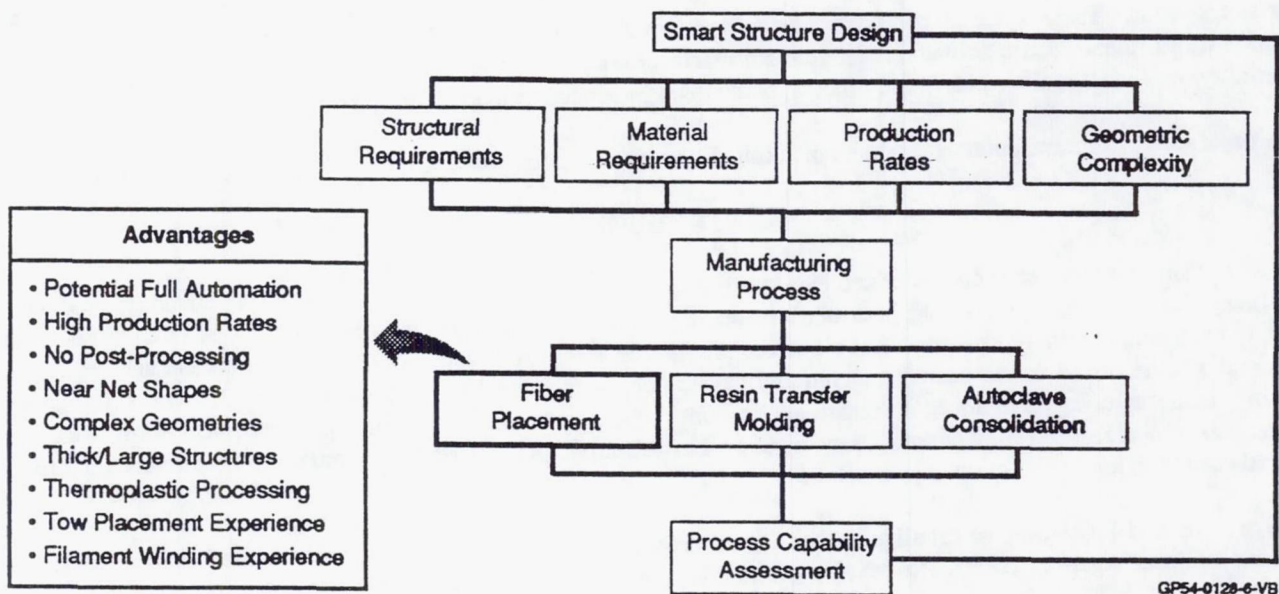


Figure 1. Smart Structure Manufacturing Flow

MDA-E has developed an integrated approach to smart structures fabrication that uses fiber placement processing. Fiber placement offers a number of advantages over more traditional composite material fabrication methods, as regards producing affordable structures. A substantial fabrication cost savings can be realized by reducing touch labor associated with ply cutting and hand lay-up of composite parts. The fiber placement process automates much of what otherwise would be touch labor. It is a process that most manufacturers of aerospace structures are using to produce large composite structural elements such as wing skins, inlet ducts, and fuel storage tanks. Besides reducing touch labor costs, fiber placement also offers cost savings due to its capacity for producing large, unitized structures. These unitized structures minimize assembly times and reduce the likelihood of incurring rework costs due to assembly mismatch.

The fiber placement process is a localized process well suited for producing large composite parts, because the post-processing required is minimal. Composite material is consolidated at the "nit" point, where the new material and previously consolidated materials fuse together under high temperature (induced by a laser source) and high pressure (induced by a compaction roller). Figure 2 illustrates the basis for fiber placement. This material spends a very short time at the nit point temperature. This short time is compensated for by increasing the temperature and pressure over those of standard processing parameters for autoclave curing. The challenge of embedding sensors and actuators in a fiber-placed article is that the active elements must withstand higher localized temperatures and pressures than those of standard material processing in the autoclave.

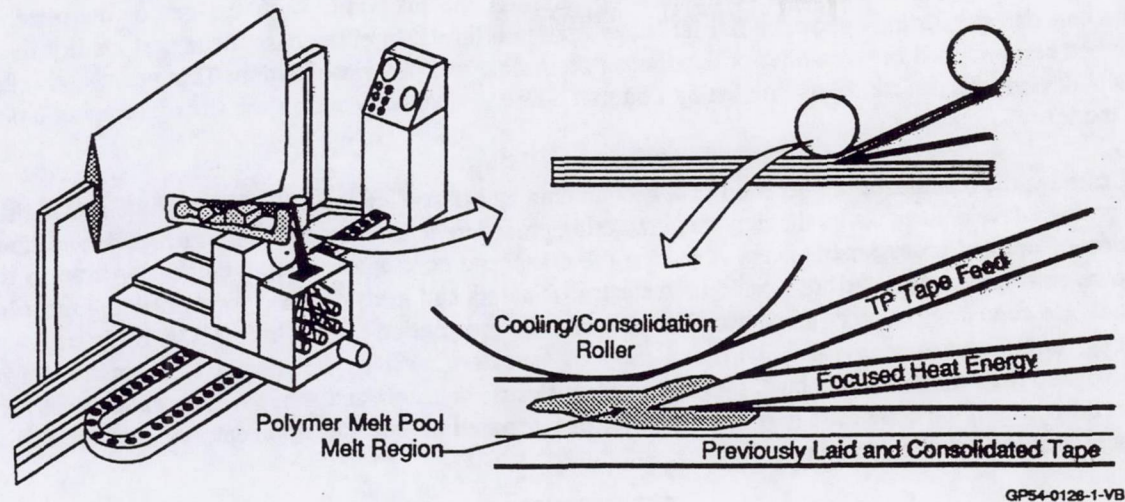


Figure 2. Fiber Placement Process

The heat source selected for processing of composite material is a 1kW Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) solid state laser. Target processing temperatures are achieved as the laser energy is absorbed by the carbon reinforcement fibers. This absorption results in a thorough heating of the graphite-resin composite material. Pressure, like temperature, is a processing parameter that is adjusted to compensate for the short time that material undergoing consolidation spends at the nit point. The fiber placement process uses a steel roller, driven by pneumatic cylinders, to produce the pressure needed for consolidating the composite material. Over the area of compaction, the localized pressure is approximately ten times that of the highest pressure commonly used during autoclave processing. The intense localized pressure becomes a manufacturing issue, especially during the embedding of sensors and actuators: This pressure can crush or break the active elements in the absence of a sufficiently robust design². A discussion of this design—in following sections—covers the topic of active element survival in greater detail. The fiber placement machine head, including the laser delivery system and the compaction roller, is shown in Figure 3:

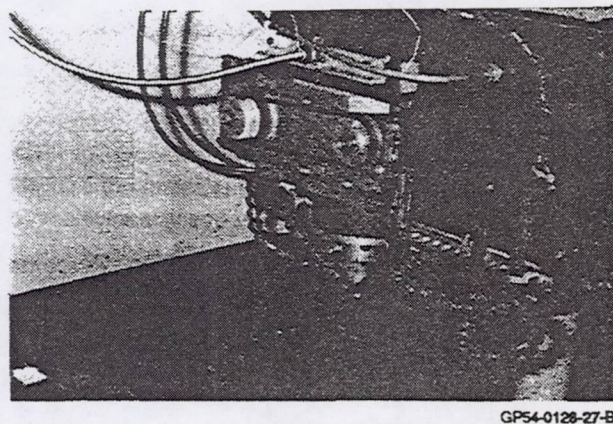
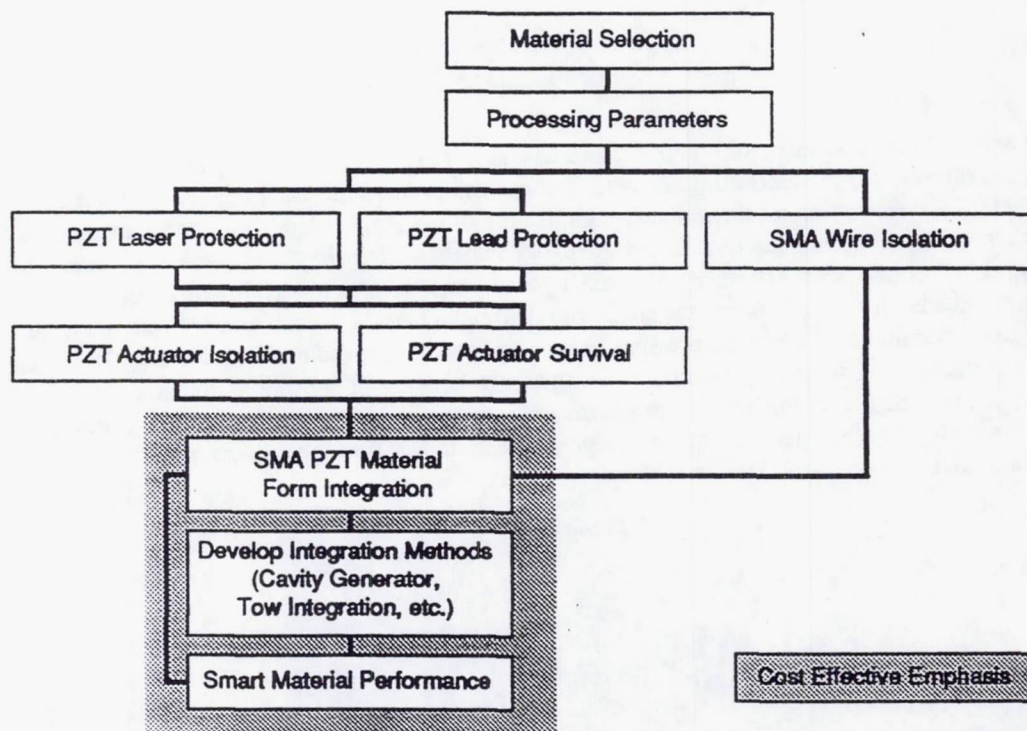


Figure 3. Fiber Placement Machine Head and Compaction Roller

A carbon fiber directional heat flow effect, combined with non-uniform thermal sink properties resulting from the mandrel and its substructure, require a feedback control system to maintain proper processing temperature. A weighted least-squares based "neuro-controller," incorporating output from an infrared camera as its controlled variable,

manipulates the laser power to maintain optimum temperature at the nit point. With the neuro-controller, nit point temperature can rise significantly above or fall far below optimum levels. In either case, poor part quality results, with either scorched resin trapped between plies or insufficient resin flow and ply consolidation. This neuro-controller, in the event of its poor performance, can be overridden by a human operator who then controls the fiber placement process in an open-loop mode.

Figure 4 illustrates the manufacturing decision flow encountered by MDA-E on the SPICES program, and highlights the integrated product development issues that any manufacturing procedure must encounter. After towpreg selection and the determination of optimal process parameters involving the composite development issue, emphasis shifts to the active elements to be embedded within the composite. Piezoelectric actuators and leads destined for embedding must be able to withstand adverse conditions, such as those from the laser and the compaction roller. Since MDA-E is using a graphite-resin towpreg, both shape memory alloy wire and the PZT actuators must be electrically (and, in the former case, thermally) isolated from the composite host. Developing piezoelectric actuators and shape memory alloy wire that can be readily embedded within the composite part is the essence of integrated product development, and also typifies the "cost effective" aspect of the SPICES program.



GP54-0128-7-VB

Figure 4. Manufacturing Decision Flow for Fiber Placement

3. FIBER-OPTIC EMBEDDING

Of all the active elements now embedded within fiber-placed smart structures, fiber-optic sensors are arguably the most fragile. Fiber optics cannot be edge egressed, since they would be irreparably damaged upon trimming of the structure edges. As such, fiber optics must be surface egressed. But if a hole is merely drilled into the composite material, the fiber optic would enter the part interior at a right angle to the part surface. At that egress point, the fiber optic would never survive a pass of the compaction roller. MDA-E has developed a procedure for preparing the egress point, such that the fiber optic at the egress point does not rise above the outer part surface. The properly prepared egress point accommodates the fiber optic, such that the latter is no longer vulnerable to the compaction roller during fiber placement. Figure 5 illustrates a surface egressed fiber-optic sensor embedded within plies of a composite structure. A final risk to egressed

fiber optics occurs where the mandrel is broken down, and the smart structure is removed from the mandrel. At no point during the breakdown must the fiber optics be supporting the composite part on a mandrel section. Care must also be taken when the mandrel sections containing egress holes are removed from the interior of the part, lest a section snag and shear an egressed fiber optic from its composite material host.

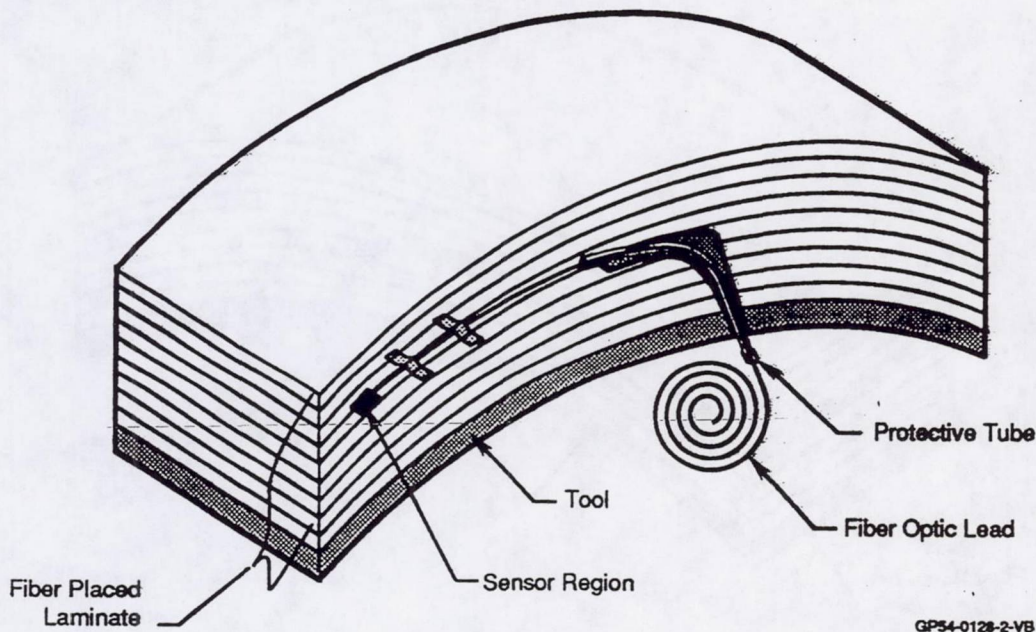


Figure 5. Surface Egress for Fiber-Optic Sensor Embedding

In addition to those embedded during the SPICES program, MDA-E has successfully embedded³ extrinsic Fabry-Perot, intrinsic Fabry-Perot, and Bragg grating sensors (for use in several health monitoring applications) using the process just described.

4. SHAPE MEMORY ALLOY EMBEDDING

As with the fiber optic sensors, shape memory alloy (SMA) material cannot be edge egressed due to the damage which would be caused to the part after trimming. Hence, surface egress techniques are again required for effective integration. SMA is a specialized material that can change its shape and effective stiffness in response to temperature change. This temperature change is usually created in the material through electrical resistance heating. If SMA is to be embedded in a graphite fiber-placed part, it must be electrically and thermally isolated from the graphite in the composite material. This need has given rise to the concept of the SMA tow. The tow consists of SMA wires embedded within an electrically and thermally isolating thermoplastic polymer for compatibility with the SPICES host materials. By design, the SMA tow width and thickness are to be the same as the composite towpreg width and thickness. Such design heightens compatibility between the SMA tow and the fiber-placed smart structures that will contain it—this design offers a prime example of integrated product development. It is planned that these “smart” tows be fed directly into the fiber placement head assembly for automatic lay-down and consolidation.

Up to five tows at a time have been used to make SPICES fiber-placed smart structures. When SMA tows are to be embedded, however, only one composite towpreg is used in fiber placement. Unlike fiber optics, which are thin enough to lie flush against the part surface without disturbing compaction, the SMA tows cannot merely lie flush upon the part surface. Due to SMA thickness, provisions must be made to preclude the SMA tow from disturbing the next ply of towpreg to be placed. The provision must be made for omission of one composite tow in a ply to make room for subsequent insertion of an SMA tow. That ply, after this provision is made, takes the appearance of a “barber pole” in the

90° orientation, because a spiral is made visible by the missing tow. This missing tow serves as the host for the SMA tows. A two-part adhesive is used to place the SMA tows; these tows are then surface egressed through rectangular slots in the composite part and in the mandrel. Figure 6 provides an illustration of SMA tow integration:

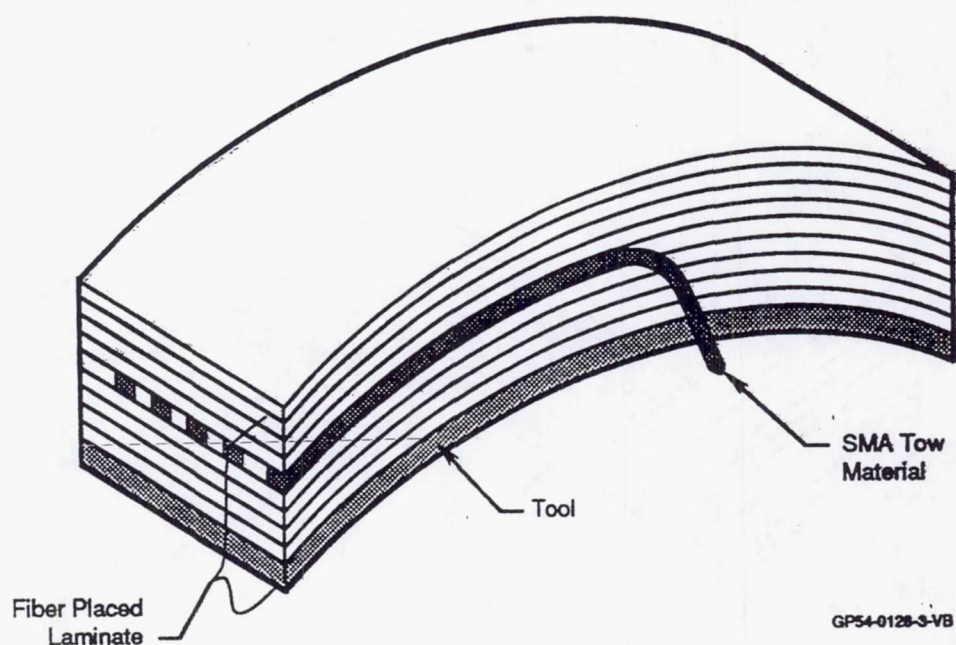


Figure 6. SMA-Tow Integration

A major concern with embedding SMA tows involves tow orientation. Currently on the SPICES trapezoidal parts, SMA tows are placed in the 90° (hoop) orientation, and the composite ply to go atop the SMA tow must be in the 0° orientation. Orientation is important, for if the ply atop the SMA tow were in the 90° orientation, the laser would have heated the SMA tow along its length. Heating the tow as such would activate the SMA wires within that tow during the manufacturing process, thereby rendering them useless for smart structure use. In addition, SMA tows cannot make up an entire ply, because the amount of composite for the 0°-orientation covering ply to adhere to would be minimal. The SPICES team is developing optimal percentages of SMA tow and composite pre-preg tow for combination, in order to ensure high quality consolidation and adhesion. During this process, the laser settings have to be optimized to maximize inter-ply consolidation and yet not activate the SMA tow material. Modifications to the SMA tow fabrication process by MMTI are underway to help maximize the exposure temperature capability of the SMA wires.

5. PIEZOELECTRIC ACTUATOR AND ACCELEROMETER EMBEDDING

The SPICES program is currently evaluating two types of piezoelectric actuators for fiber placement integration. These include a stacked PZT within a titanium protective frame developed by Pennsylvania State University⁴, and a version of ACX plate-type PZT actuators. Piezoelectric actuators in general are electromechanically coupled materials which are very brittle and require electrical isolation. In addition, the wires from the actuators must be isolated from the high temperature and compaction roller pressure of the fiber placement process. As with the fiber optics and SMA, edge egress of lead wires is difficult due to part trimming.

PZT actuators and miniature accelerometers are the largest, both in area and in thickness, of the active elements to be embedded in SPICES fiber-placed smart structures. Both the stacked PZT and plate-type PZT must occupy a far larger volume within the host structure than fiber optics or shape memory alloy tows. Both fiber optics and SMA tows have embedding procedures associated with them, as discussed earlier. The procedures for embedding PZT actuators and accelerometers call for the removal of much more composite volume from a part, within a highly concentrated region.

Three methods—the placement-driven method, the cut-out method, and the routing method—have been used to prepare troughs for holding actuators in fiber-placed parts. The first two methods were used during the first two manufacturing phases of the SPICES program; the third, during the third manufacturing phase of the SPICES program. Figure 7 illustrates these trough-preparation methods:

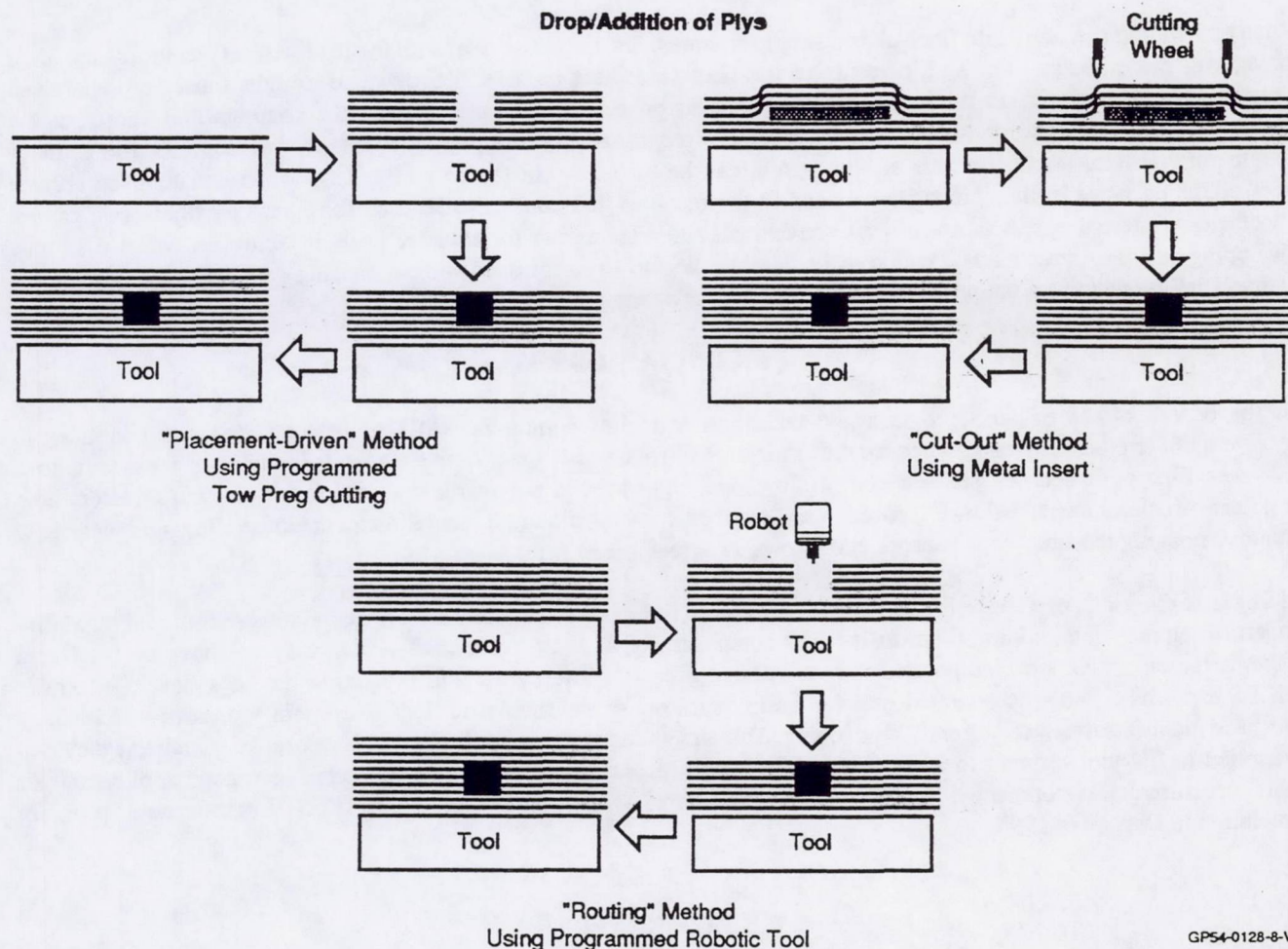


Figure 7. Methods of PZT Actuator Embedding

Each method was investigated for its cost effectiveness in terms of programming, formation, and embedding time. The placement-driven method entails determining the area and depth needed for a trough, determining how many composite plies are as thick as the depth required, and (for the required number of plies) shutting off the laser when it passes over the trough area. For each ply, unconsolidated towpreg is then cut away to create the trough. This method was successful in making viable troughs for actuator embedding, but requires extensive programming time of the fiber-placement machine and additional hands-on work to clean up the surfaces. By contrast, the cut-out method involves the use of a "shim" in the area of the actuator to be embedded. The shim is put in the area where the embedded element is to be placed, on the ply that represents the bottom of the trough. Fiber placement then proceeds as usual, until the thickness of the plies covering the shim corresponds to the trough depth. A router or a similar drill-based device is then used to cut through the composite tows to the shim. All composite material above the shim is removed in this manner, and the shim itself is then removed. This method is less time consuming in terms of programming time required, but still requires more touch labor to cut out the shim. It also can also lead to delaminations within the composite part due to the step the tows must take over the shim.

For use in the third phase of the SPICES manufacturing development, a trough preparation method that makes use of an external composite cutting tool programmed for any cavity length, depth, or width has been used. Initial results of this "routing" method show that a trough of actuator size can be created five times faster than the other two methods, with no additional hands-on trimming afterwards. In addition, the cutter is programmable from a standard personal computer for easy operation. Once the actuators are placed in their troughs, appropriate coatings are used to protect them from the laser energy during material roll-over.

When embedding actuators into fiber-placed smart structures, one must also deal with the lead wires. Current off-the-shelf wiring will not withstand the high pressure of the fiber placement process. Narrow wire troughs must be prepared to accommodate these wires, to minimize any load transfer on them which could crack the coatings and short out the electrical circuit. SPICES has shown that by using the programmable "routing" method, as was done for the actuator troughs, any length, depth, or path of wire egress can be made within the part. The lead wires can then be surface egressed, using holes in the composite part and in the mandrel that could also be used for egressing fiber optic cables. Nonetheless, internal egress is not always convenient, and edge egress for actuator leads is desirable. MDA-E is now developing an edge egress method which will still allow the part to be trimmed without causing damage to the wires. This method shall prove to be a unique alternative to the surface egress method now in use.

6. CONCLUSIONS

For the benefit of the SPICES program and the smart structures community, MDA-E has tailored and continues to improve its fiber placement procedures for the fabrication of smart structures. Active elements included in these structures have been fiber optic sensors, shape memory alloy wires embedded in polymeric tow, two forms of PZT actuators, and miniature accelerometers. MDA-E procedures, described herein, allow for active element embedding and egressing without damaging the fiber-optic sensors, SMA tows, or actuator lead wires.

Adding troughs, slots, or gaps to a conventional composite has an adverse effect on its "material" strength and durability properties. Nonetheless, adding them to the host composites of a smart "structure" system may not have such adverse effects if the additions are incorporated into the design process². The egress and protection methods developed under SPICES auspices can be incorporated into full-scale thermoset or thermoplastic fiber placement processes which many aerospace manufacturers are currently developing. These methods are also not limited to break-down mandrels; they can be applied to flat tool surfaces to fabricate fuselage panels, access doors, wing skins, or other aerospace applications of smart structures. Development of manufacturing procedures will continue on the SPICES program until program completion in December 1995.

7. BIBLIOGRAPHY

1. J.H. Jacobs, "Integrated Design and Synthesis of Smart Material Systems—An Overview of the ARPA SPICES Program," SPIE 2447-19, 1995 North American Conference on Smart Structures and Materials, San Diego, CA, March 1995.
2. R. M. Hauch, "Finite Element Modeling of Composite Structures with Embedded Actuators," SPIE 2443-50, 1995 North American Conference on Smart Structures and Materials, San Diego, CA, March 1995.
3. J. Belk, K. Rupel, E. Baumann, G. Springer, T. Story, J. Andrews, B. Johnson, J. Haake, and R. Pulfray, "Embedded Sensors for Submarine Structures (ES³)," Quarterly Interim Technical Report for Period 1 January to 31 March, Contract MDA972-90-C-0026, St. Louis: McDonnell Douglas Corp., 1993.
4. G. Koopmann, S.K. Kurtz, G.A. Lesieutre, S. Yoshikawa, W. Chen, J.B. Fahnline, S.P. Pai, and B.R. Dershem, "Design of an embedded piezoceramic actuator for active control applications" SPIE 2444-53, 1995 North American Conference on Smart Structures and Materials, San Diego, CA, March 1995.

514-27

ABS ONLY

61449

**Performance of Integrated Fiber Optic, Piezoelectric, and Shape
Memory Alloy Actuators/Sensors in Thermoset Composites**

235100

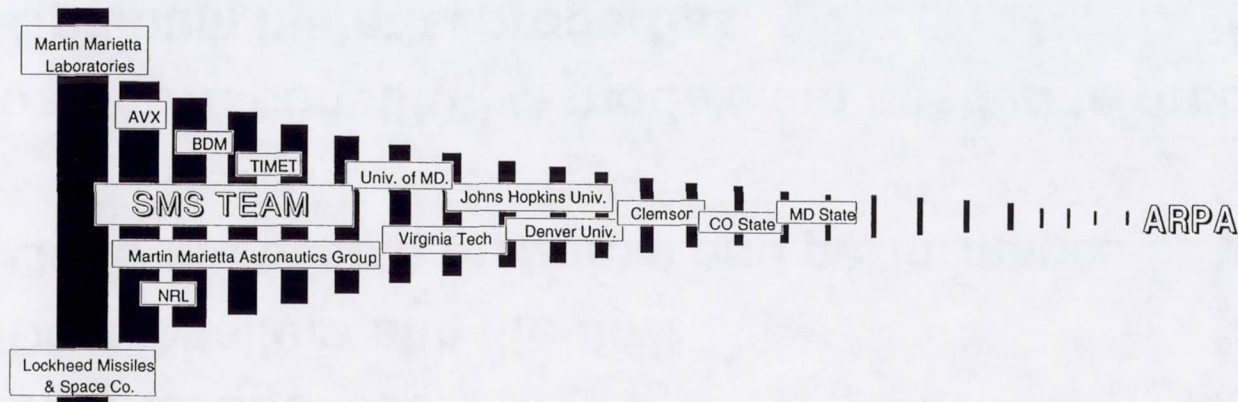
C. Michael Trottier
Fiber Materials, Incorporated
Biddeford Industrial Park
Biddeford, ME 04005

1P

Recently, scientists and engineers have investigated the advantages of smart materials and structures by including actuators in material systems for controlling and altering the response of structural environments. Applications of these materials systems include vibration suppression/isolation, precision positioning, damage detection and tunable devices. Some of the embedded materials being investigated for accomplishing these tasks include piezoelectric ceramics, shape memory alloys and fiber optics. These materials have some benefits and some shortcomings; each is being studied for use in active material design in the SPICES (Synthesis and Processing of Intelligent Cost Effective Structures) Consortium. The focus of this paper concerns the manufacturing aspects of smart structures by incorporating piezoelectric ceramics, shape memory alloys and fiber optics in a reinforced thermoset matrix via resin transfer molding (RTM).

Page intentionally left blank

Finite Element Modeling of Electrostrictive Ceramic Actuators and Sensors



Craig L. Hom and Natarajan Shankar

MCA Modeling - The Need

MCA design codes are needed to predict:

- Internal stresses
- Device failure and life-time
- Optimum device response and performance



Electrostrictive constitutive models are needed to predict:

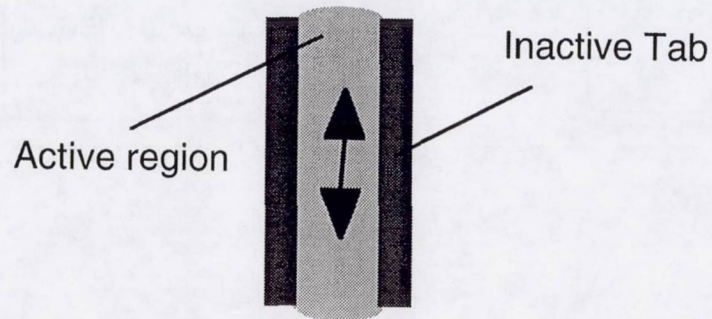
- Optimum material properties
- Electro-mechanical interaction
- Coupling coefficient
(an important system parameter)



MCA Modeling - the SMS Impact

BEFORE

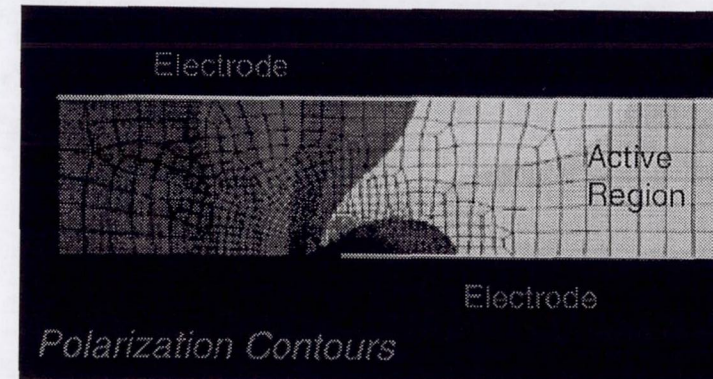
Thermal Analog Model



- Good displacement predictions
- No electric field modeling
- No prestress effects
- High stresses predicted, but failure could not be predicted
- No defect analysis

AFTER

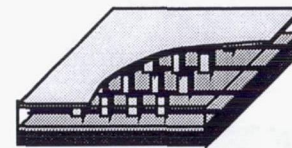
Fully Coupled Model



- Good displacement predictions
- Electric field distribution modeled
- Prestress modeled
- Fracture mechanics to predict failure
- Critical defects analyzed

MCA Modeling Roadmap

Thermal analog model



Composite array analysis

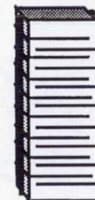
- Interface stresses
- Surface displacements

Electrostrictive constitutive model

Finite element actuator model

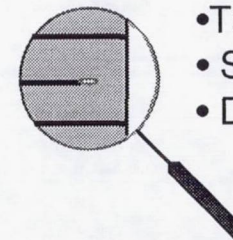


- Full coupling
- Prestress effects
- Coupling coefficients



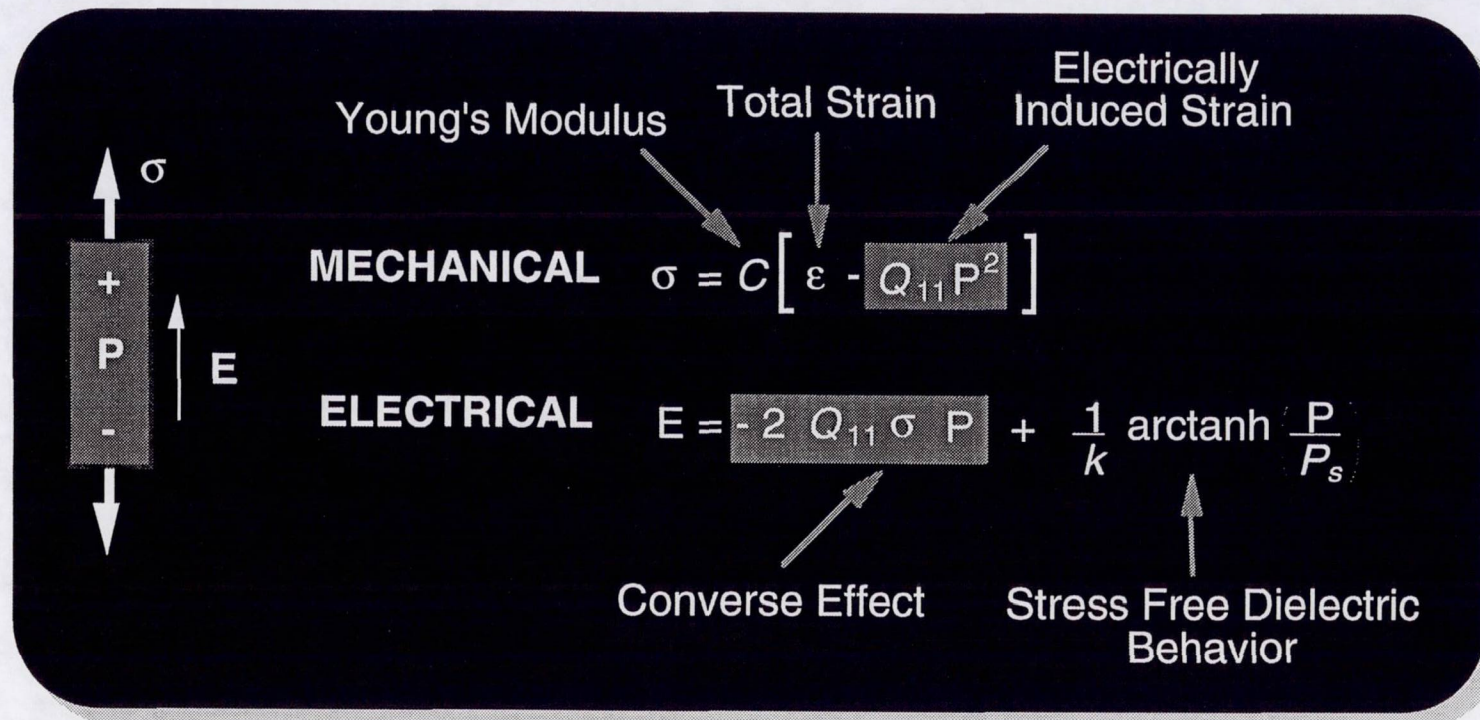
- Layer stresses
- Fringe effects
- Displacement response

Fracture mechanics



- Tab cracks
- Slit design
- Delaminations

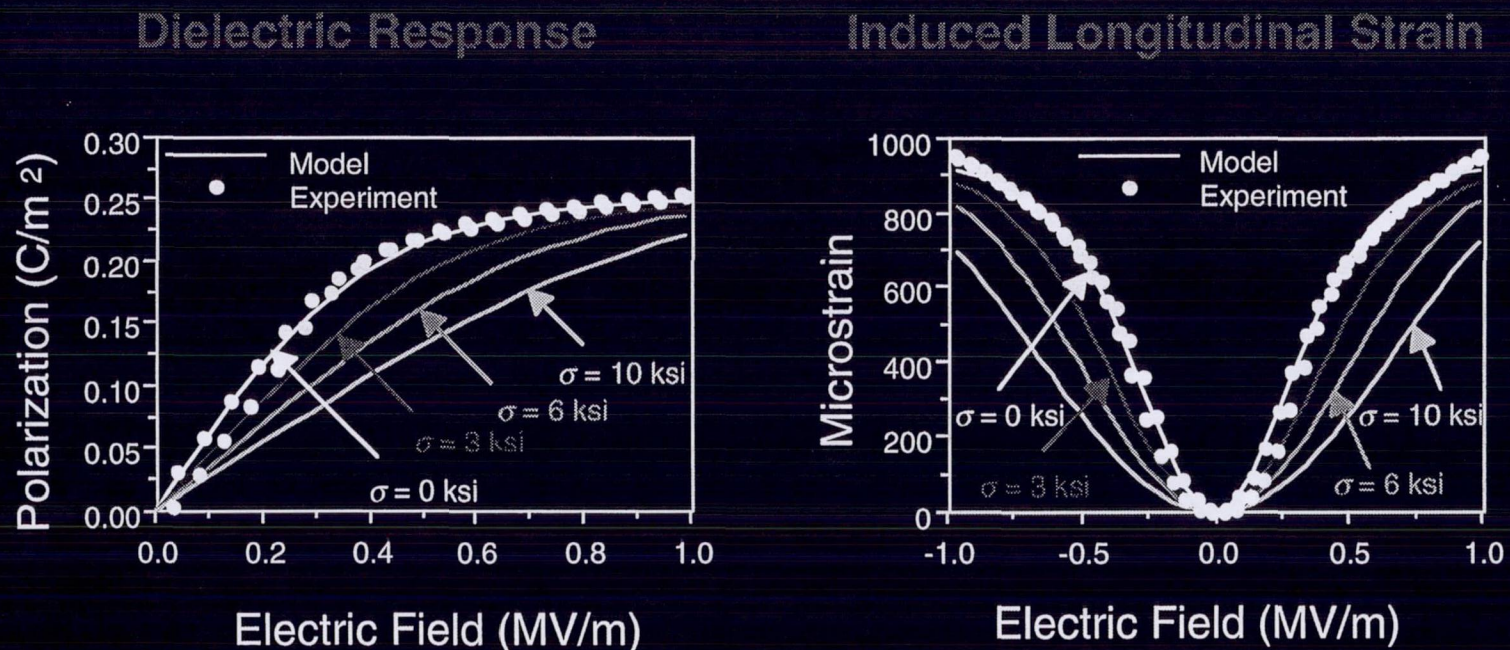
Constitutive Model Formulation



- Full coupling of mechanical and electrical behavior
- Models polarization saturation
- Extended to 3D behavior

Constitutive Model Behavior

PMN-PT-BT b200120 @ 20°C and 1 Hz

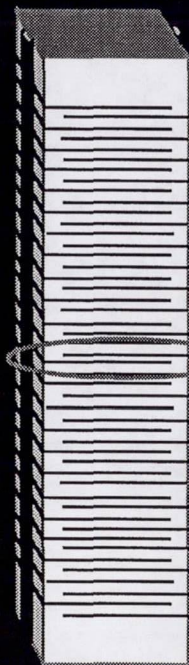


Model parameters obtained from stress-free behavior

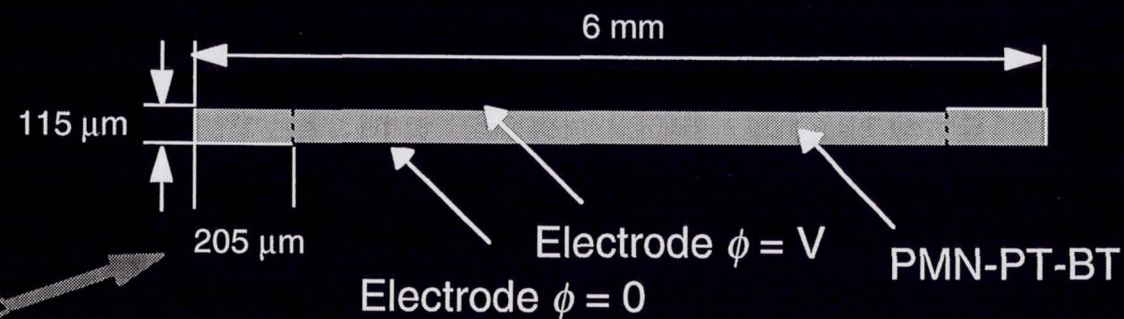
$$P_s = 0.253 \text{ C/m}^2, k = 2.50 \text{ m/MV}, Q_{11} = 0.0147 \text{ m}^4/\text{C}^4$$

Multilayered Actuator Analysis

Device Configuration



2D Unit Cell Model



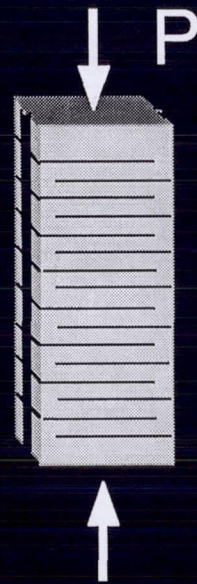
Analysis at layer level

2D plane strain, nonlinear analysis

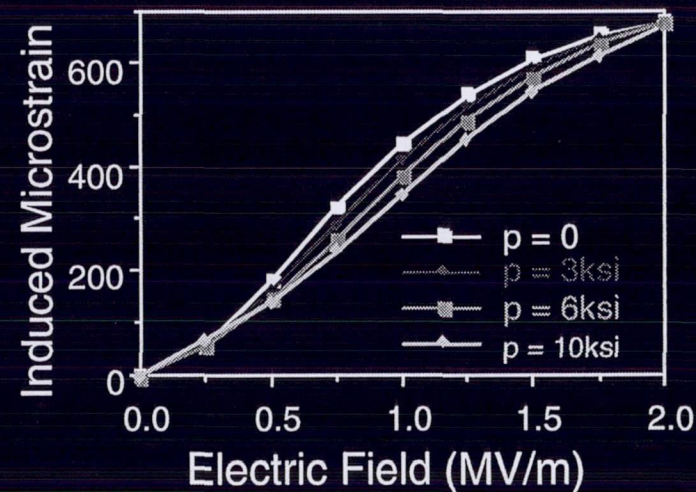
Stress in tab region predicted

Actuator Strain Response

Prestressed Actuator



Finite Element Results



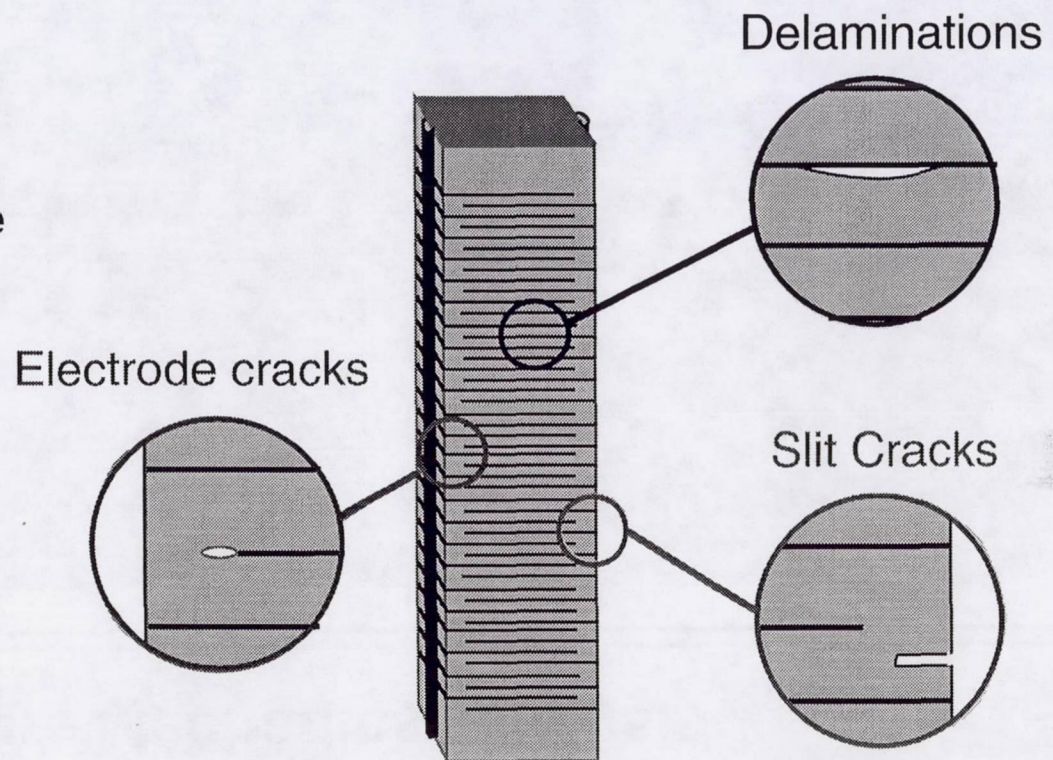
Prestress effects polarization

Polarization effects strain response

14% drop in strain at 1 MV/m and P = 6 ksi

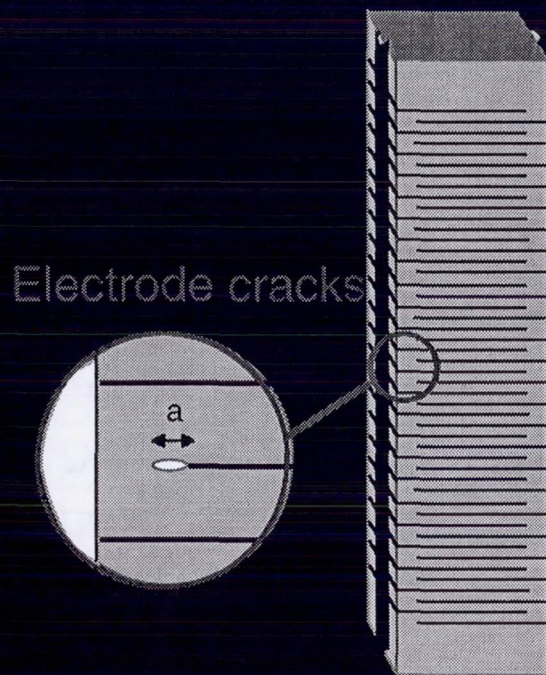
Fracture Mechanics Analysis

- Three types of defects identified
- Detailed finite element analysis of each flaw
- State-of-art fracture mechanics for electrostrictors employed

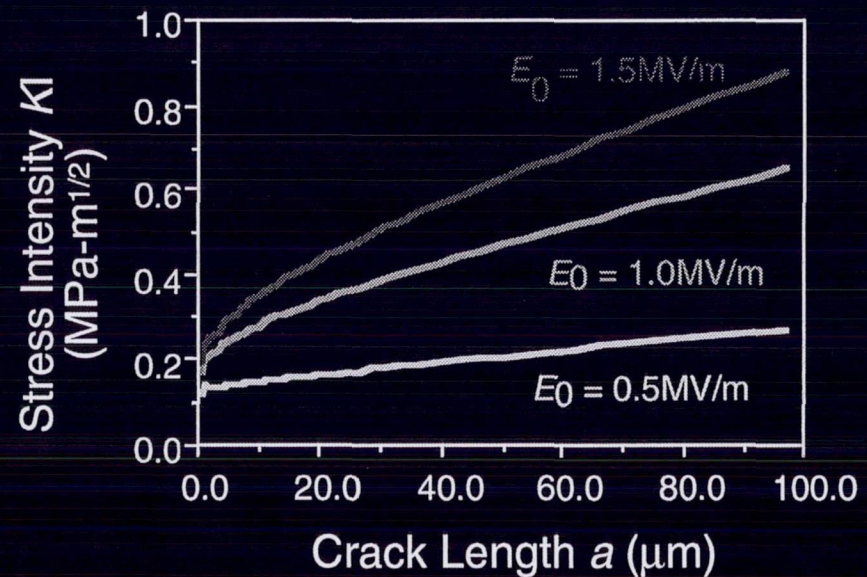


Fracture Mechanics Analysis

Electrode Crack in Tab



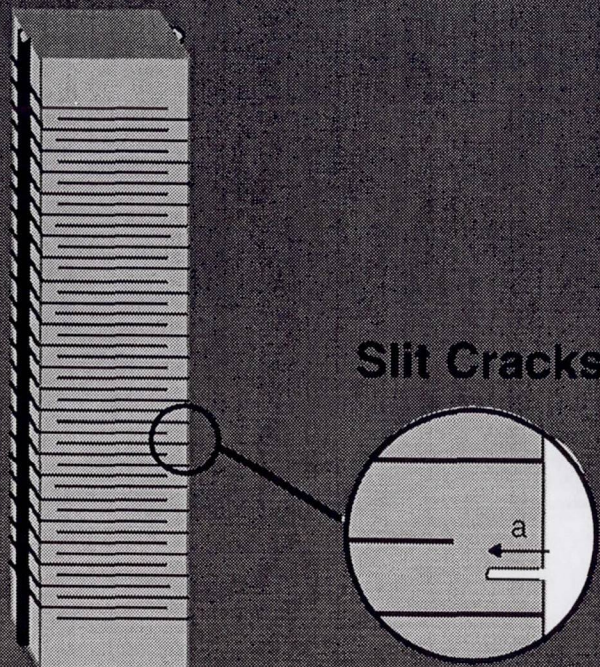
Finite Element Results



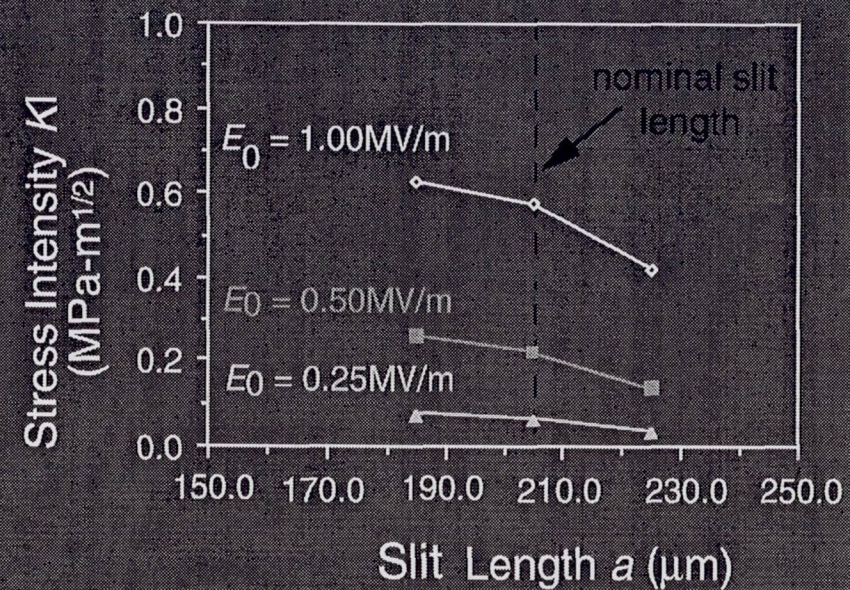
- Fracture toughness of PMN ~ 0.9 MPa-m^{1/2}
- Current AVX actuator design is stable

Fracture Mechanics Analysis

Slit Crack in Tab



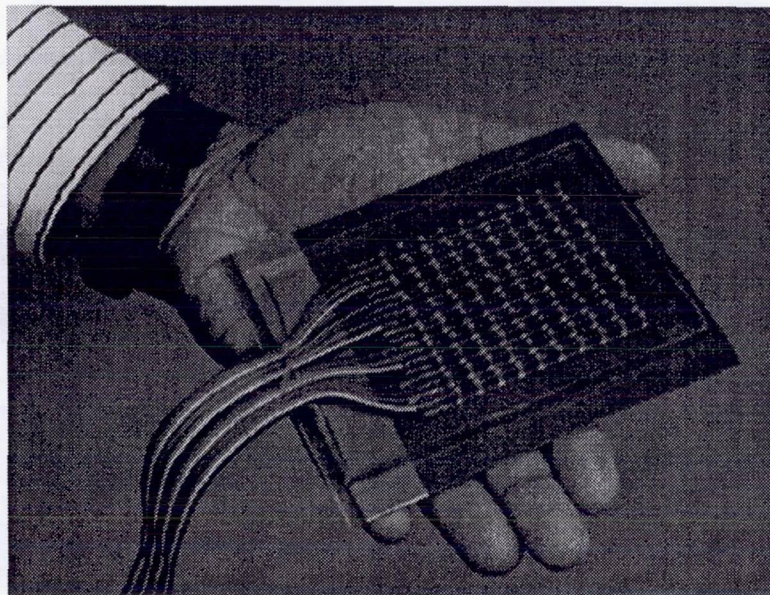
Finite Element Results



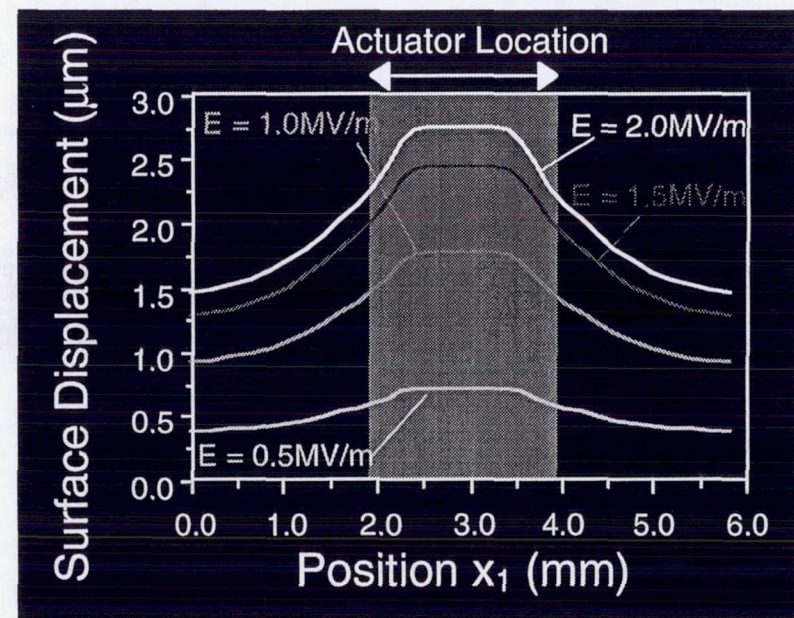
- Fracture toughness of PMN $\sim 0.9 \text{ MPa-m}^{1/2}$
- Current AVX actuator design can be improved

1-3 Composite Array Analysis

Composite Device



Finite Element Results



- 2-D plane stress, nonlinear FEA analysis
- 47% decrease in surface displacement in the matrix
- 17% decrease in displacement at actuator's edge

MCA Modeling - Conclusions

Finite Element Model Predicts Complex Behavior

- **Polarization and strain drop with prestress**
- **Electric field fringe effects**
- **Failure via fracture mechanics**

Quasi-Static Analysis Is a Useful Actuator Design Tool

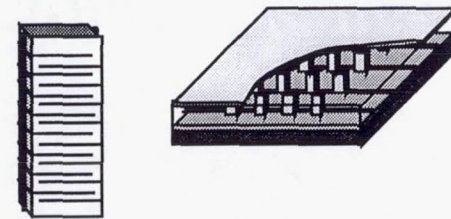
- **Minimize tab crack failures**
- **Maximize strain output**



MCA Modeling - Future

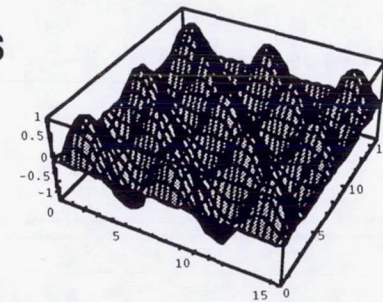
Apply Computer Models to Design CSM Actuators and Composites

- Minimize interface stresses
- Predict element interaction



1-3 Composite Analysis Extended to Dynamic Behavior

- Predict frequency response (excited modes)
- Predict dynamic coupling coefficients
- Coupled solid-fluid interaction



515-27
ABS ONLY
61452
235101

**Smart Material Demonstrators Based on Shape Memory
Alloys and Electroceramics**

Dr. Arthur V. Cooke
Martin Marietta Laboratories - Baltimore
1450 S. Rolling Road
Baltimore, MD 21227-3898, USA

1 p.

This paper describes the development and characterization of two technology demonstrators that were produced under the auspices of an ARPA sponsored smart materials synthesis and processing effort. The ARPA Smart Materials and Synthesis (SMS) Program was a 2 year, \$10M partnership led by Martin Marietta Laboratories - Baltimore and included Lockheed Missiles & Space Co., NRL, AVX Corp., Martin Marietta Astronautics Groups, BDM Federal, Inc., Virginia Tech, Clemson, University of Maryland, Denver University, and The John Hopkins University. In order to demonstrate the usefulness of magnetron sputtered shape memory foil and the manufacturability of reliable, reproducible electrostrictive actuators, the team designed a broadband active vibration cancellation device for suppressing the vibration load on delicate instruments and precision pointing devices mounted on orbiting satellites and spacecraft. The results of extensive device characterization and bench testing are discussed. Initial simulation results show excellent control authority and amplitude attenuation over the range of anticipated disturbance frequencies. The SMS Team has also developed an active 1-3 composite comprising micro-electrostrictive actuators embedded in a polymeric matrix suitable for underwater applications such as sonar quieting and listening arrays, and for medical imaging. Follow-on programs employing these technologies are also described.

Page intentionally left blank

516-06
614547
035102

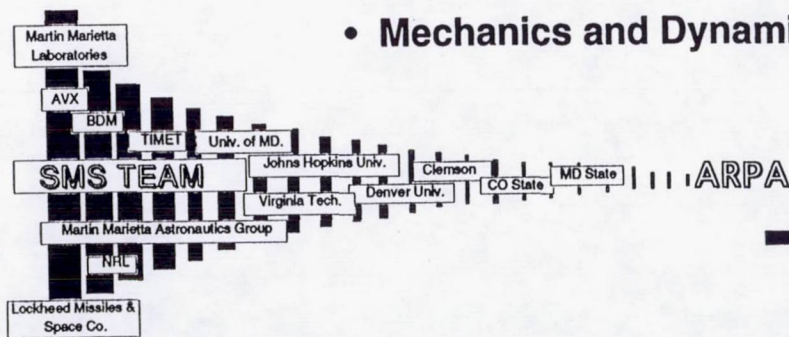
**Performance of a Smart Vibration Isolator for
Precision Spacecraft Instruments**

Marc E. Regelbrugge, Alain Carrier, and William C. Dickson
Lockheed Palo Alto Research Laboratories
Palo Alto, CA 94304, USA

02P.

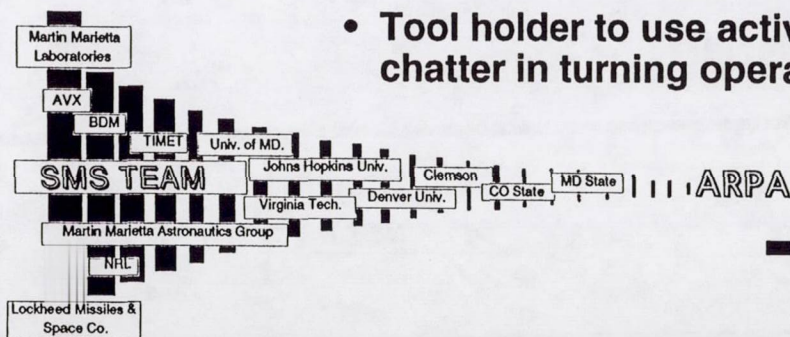
Under the ARPA SMS Partnership Program for Synthesis and Processing of Smart Materials, Lockheed Missiles and Space Company, Inc. has developed a demonstration prototype vibration cancelling mount using electrostrictive ceramic and shape-memory alloy actuators. Shape-memory actuators provide an adaptive-passive, self-damping support for isolation, while the electrostrictive actuators are employed to provide force and position control. The demonstration device was designed to address generic requirements for vibration stabilization of precision spacecraft instruments. It is reconfigurable to operate in any of four modes; passive isolation, active-passive isolation using force cancellation, active precision positioning, and active disturbance rejection. The presentation summarizes design of the device design and results of experimental evaluations of the device in isolation (active and passive) and positioning modes. Rejection of payload-borne disturbances is also discussed with reference to predictions from experimentally calibrated simulations. Finally, avenues for further development and refinement of the device are discussed.

- **Objective:**
 - Demonstrate the benefits of advances in Synthesis and Processing of Smart Materials and Structures for applications of military (and commercial) interest
- **Focus:**
 - Active Vibration Control for sensitive spacecraft instruments using an interface Active Vibration Canceling (AVC) mount for:
 - Broadband Active/Passive Isolation
 - Precision (sub- μm) Positioning
 - Disturbance Rejection
 - Incorporated Products from the entire SMS Team effort
 - Electrostrictive Ceramic stack actuators (AVX)
 - Shape-Memory alloy composite Leaf Springs (MMAG)
 - Force Cancellation control (LMSC)
 - Mechanics and Dynamics models (MML•B, VPI/CIMSS)



SMS Team

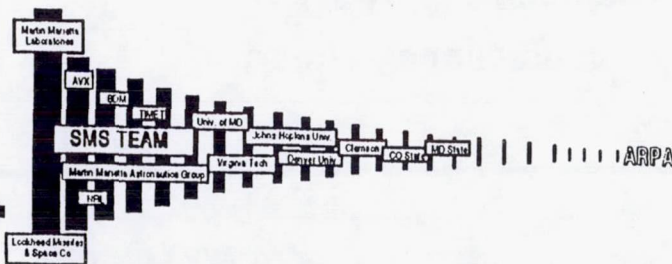
- **Define Requirements**
 - **On-Orbit excitation of jitter-sensitive spacecraft instruments**
 - **Broadband with discrete, narrow-band components**
 - **Ancillary requirements include launch loads**
- **Assess Smart Materials capabilities**
- **Design prototype Active Vibration Canceler (AVC) Mount**
- **Produce Prototype using components supplied by SMS Team**
- **Test and Evaluate Performance of AVC device**
 - **(only remaining item still in progress)**
- **Search for other promising Smart Materials applications**
 - **LMSC-led Technology Applications Committee forum**
 - **University of Maryland Smart Machine Tool Post Demonstrator**
 - **Tool holder to use active control to improve surface finish and reduce tool chatter in turning operations**



Target Application and Demonstration

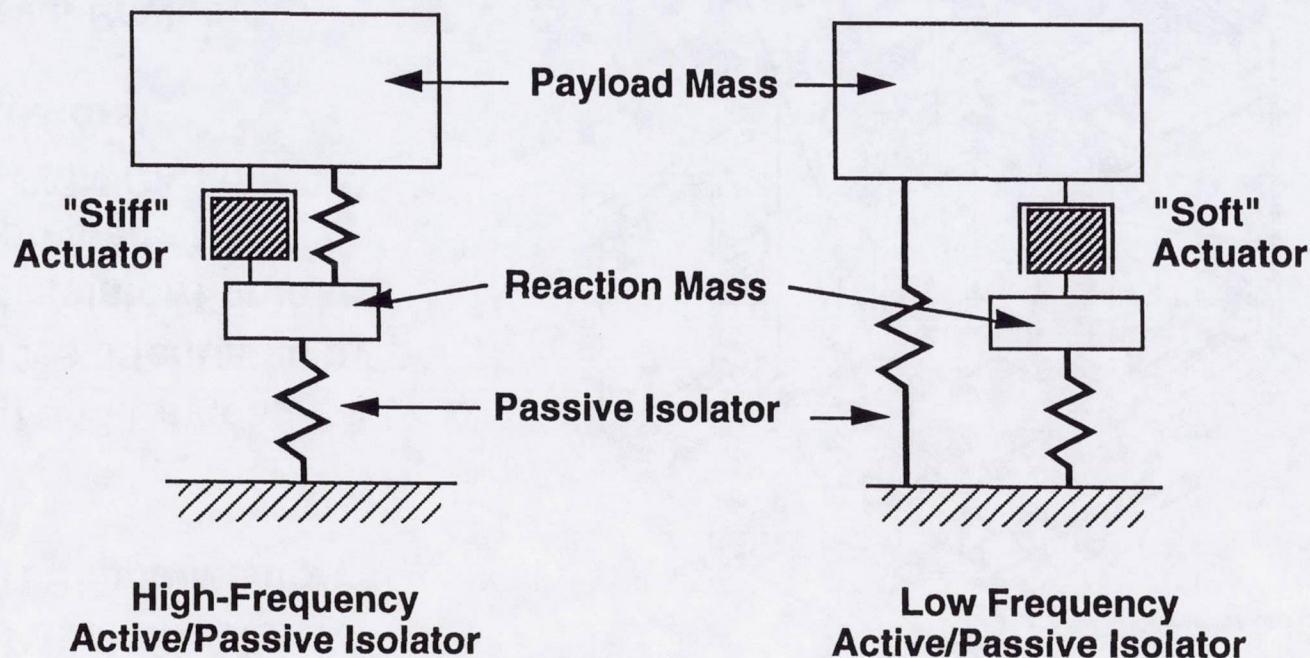
Target Application

- **Broadband isolation for spacecraft instruments**
 - Earth sensing
 - Laser communication
 - Microgravity experiments
- **Disturbance sources:**
 - Reaction wheels (5-60 Hz)
 - Cryocoolers (40-50 Hz)
 - Solar arrays (100 Hz)
 - Control moment gyros (80-100 Hz)
 - Thrusters (1-5 Hz)



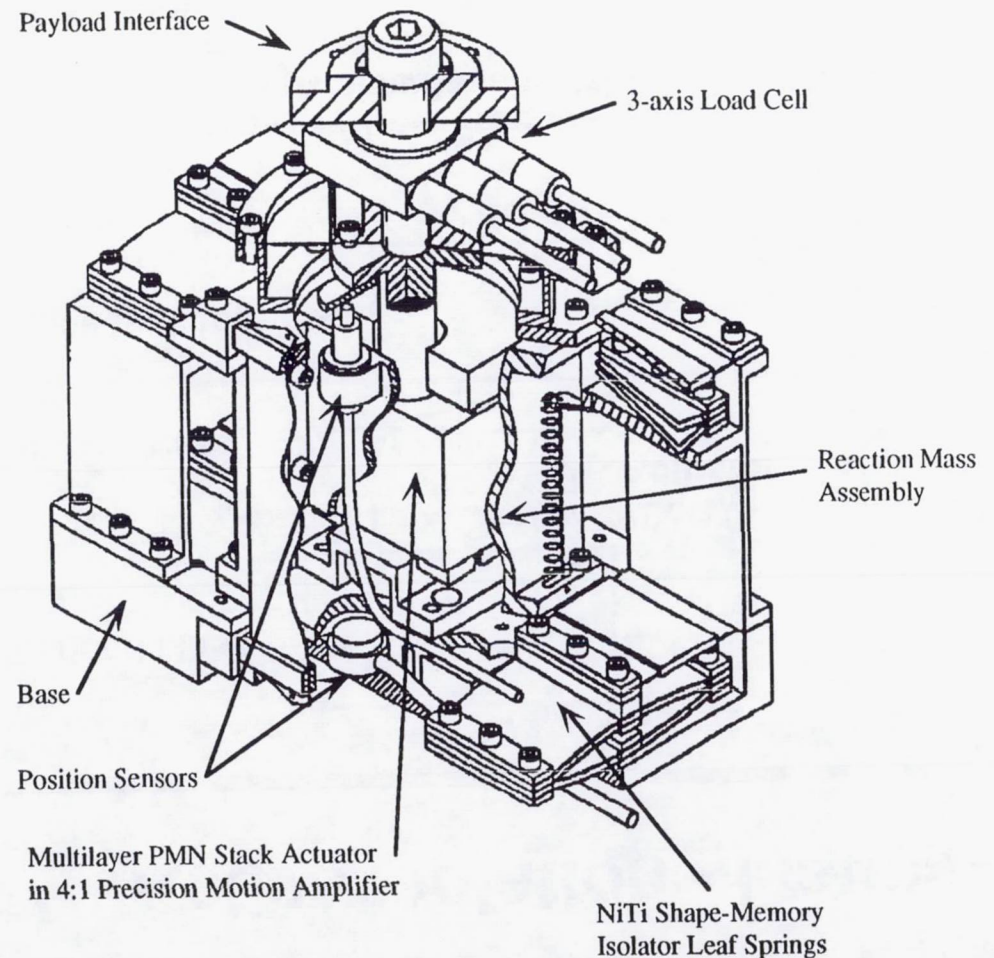
SMS Team Proprietary Information

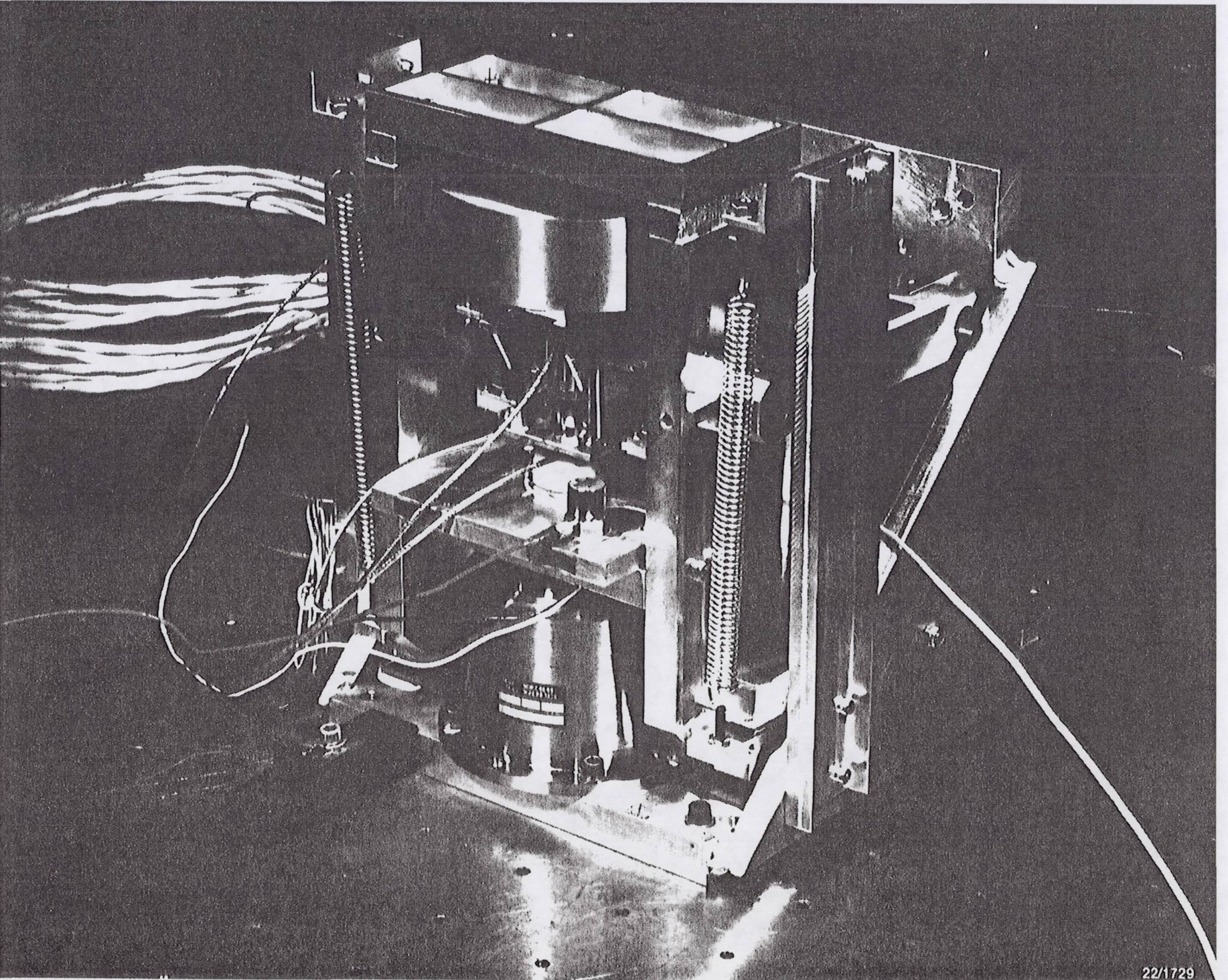
Active Isolation - Issues

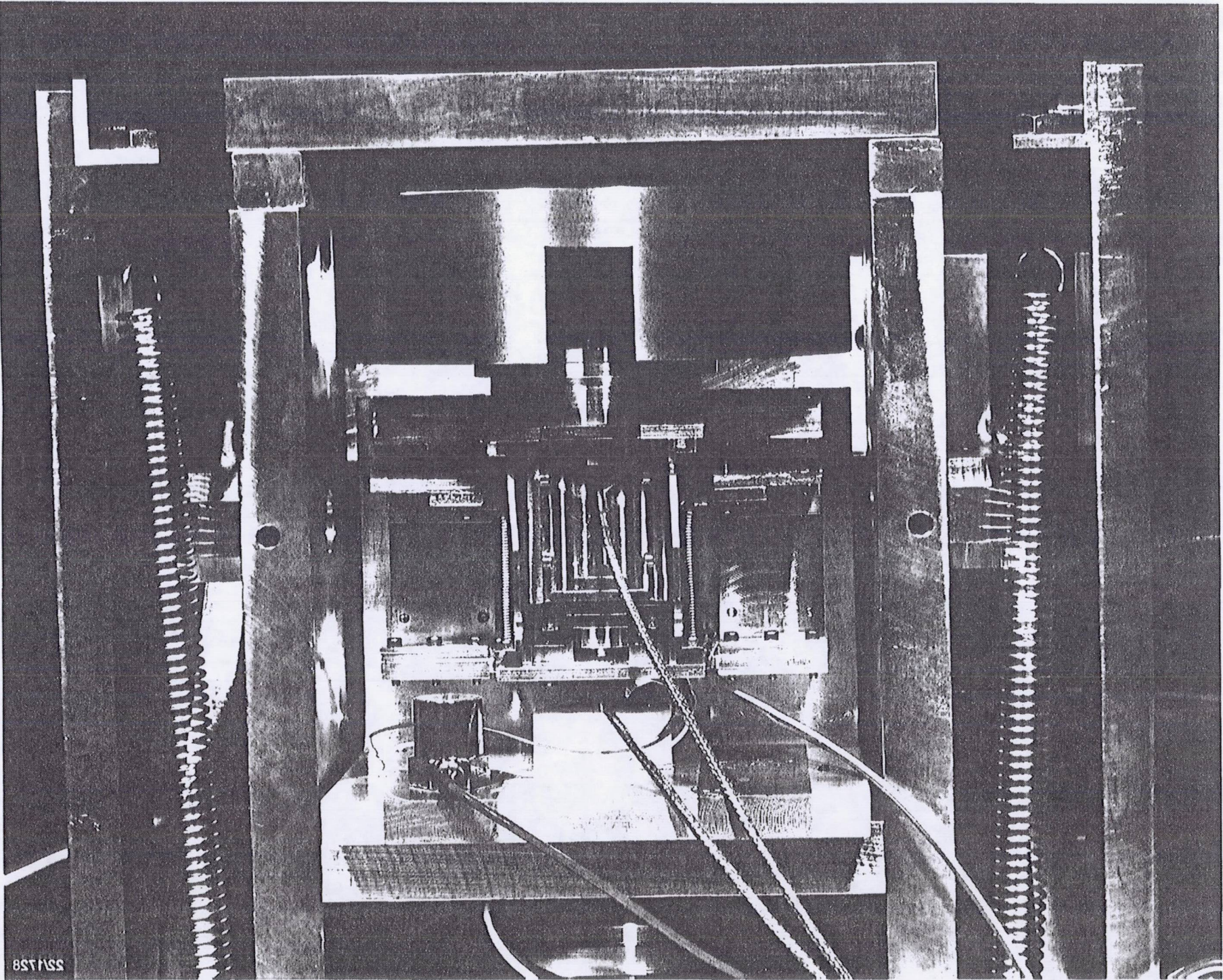


- **Passive component simplifies active control**
- **Isolator arrangement selected for application**
 - "Stiff" = low stroke/high force, "Soft" = high stroke/low force
- **Kinematics**
 - Multi-axis control for off-axis spillover
 - MIMO approaches favor robustness vs. complexity
 - Kinematic decoupling is hard

- Launch Loads mitigated by Adaptive-Passive Isolator Stage (NiTi Shape-Memory Actuators)
- Spacecraft and Payload Disturbances attenuated by combined Isolator/Force Cancellation stage (NiTi Alloy and PMN Ceramic Stack Actuators)
- Micron-Level Payload Positioning (PMN Stack Actuator)



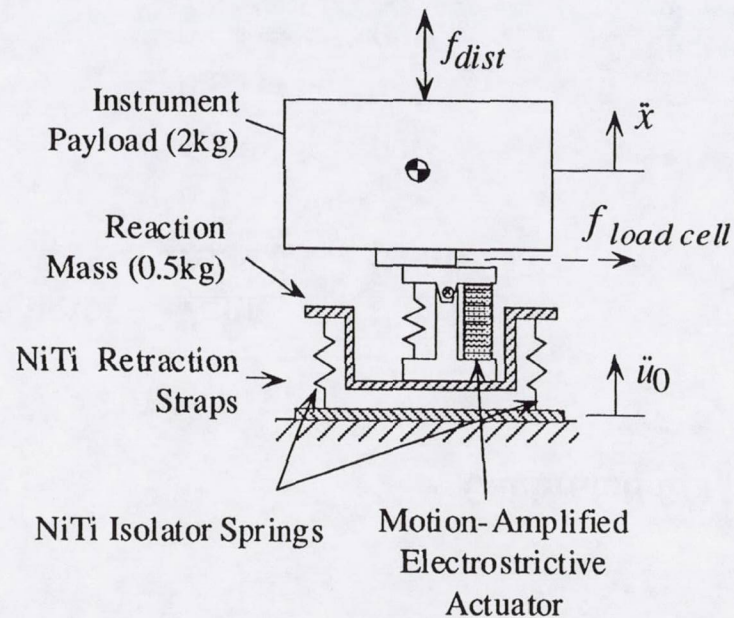




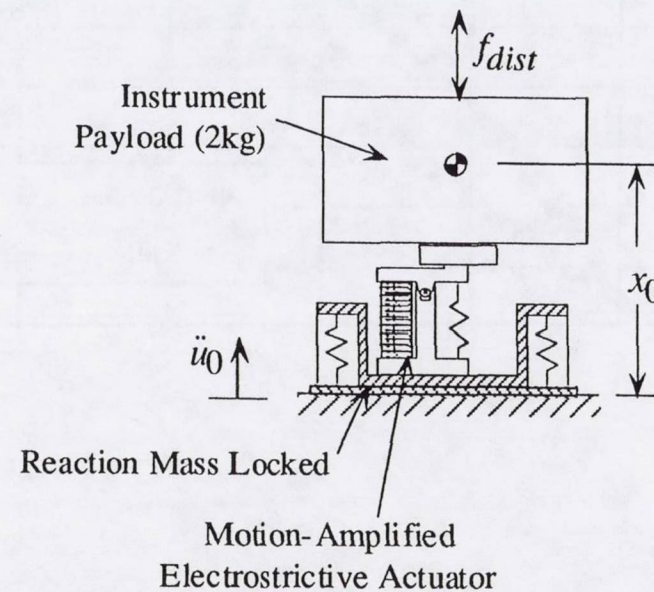
SSV158

AVC Operation

Active-Passive Isolation



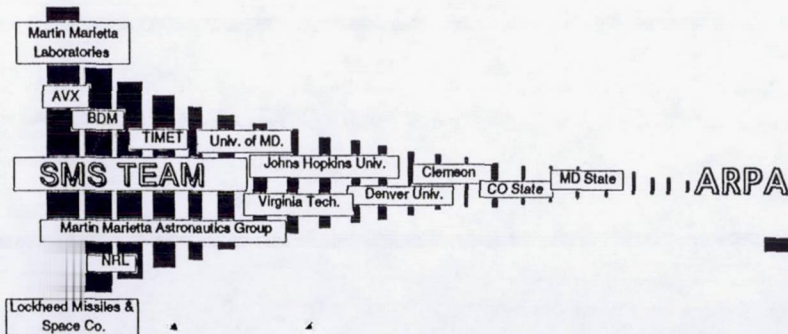
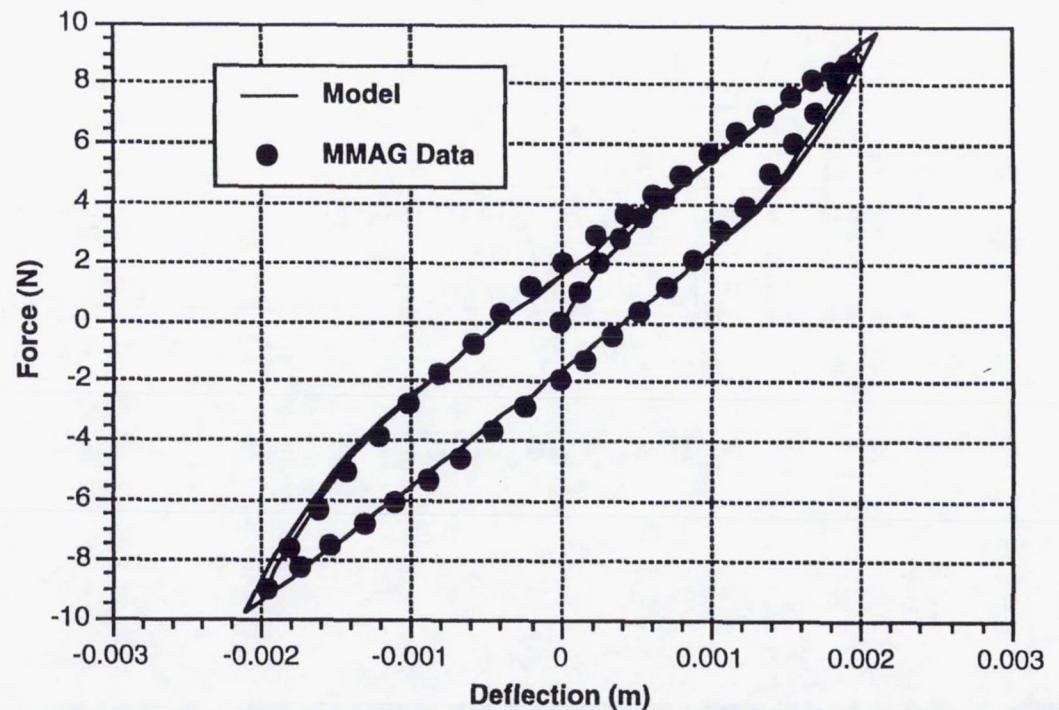
Precision Positioning



SMA Model Parameters

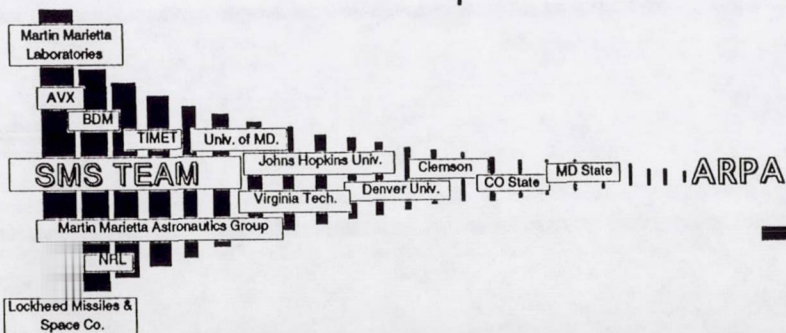
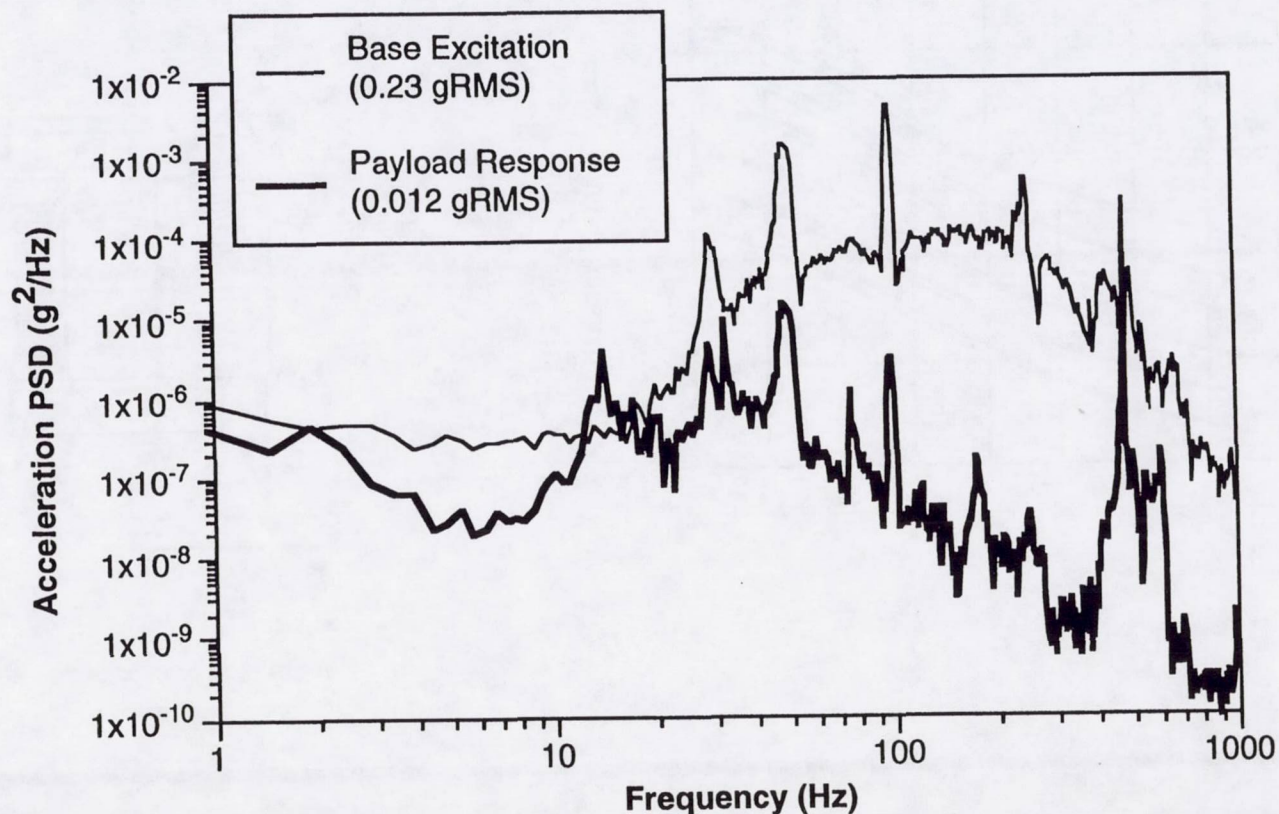
- Calibrated to MMAG Measured Data

Parameter	Value	dimension
E	7529.03	(N/m)
ν	0.0	
Y	5.338	(N)
α	0.9311	
f_t	0	(N)
c	0	
a	0	
n	2	

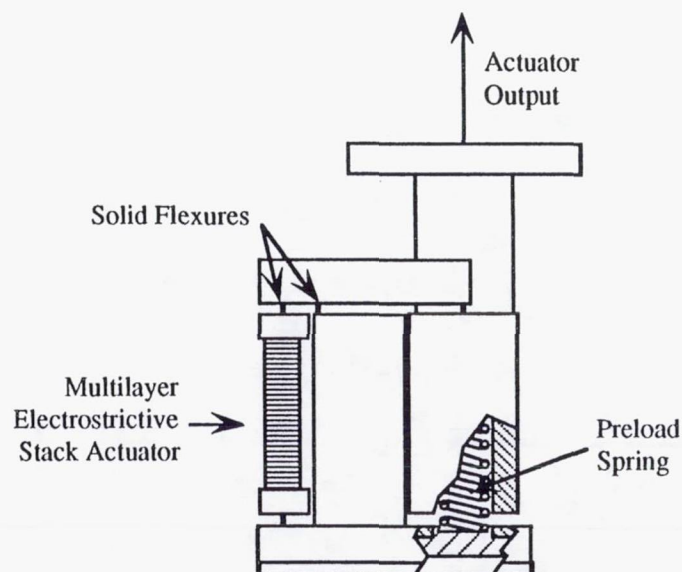


AVC Open Loop Performance

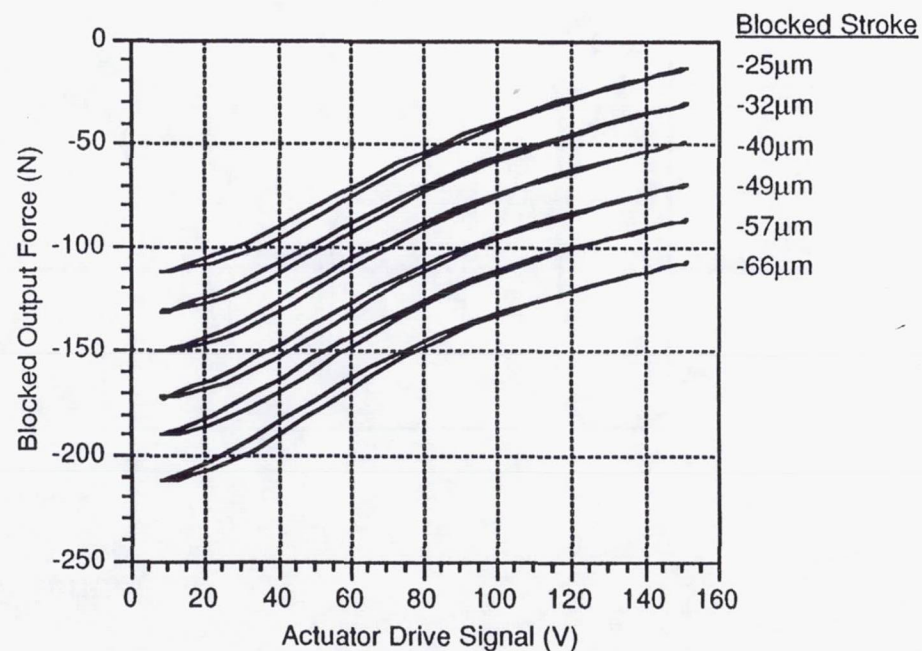
- Bottom Line: Disturbance Attenuation

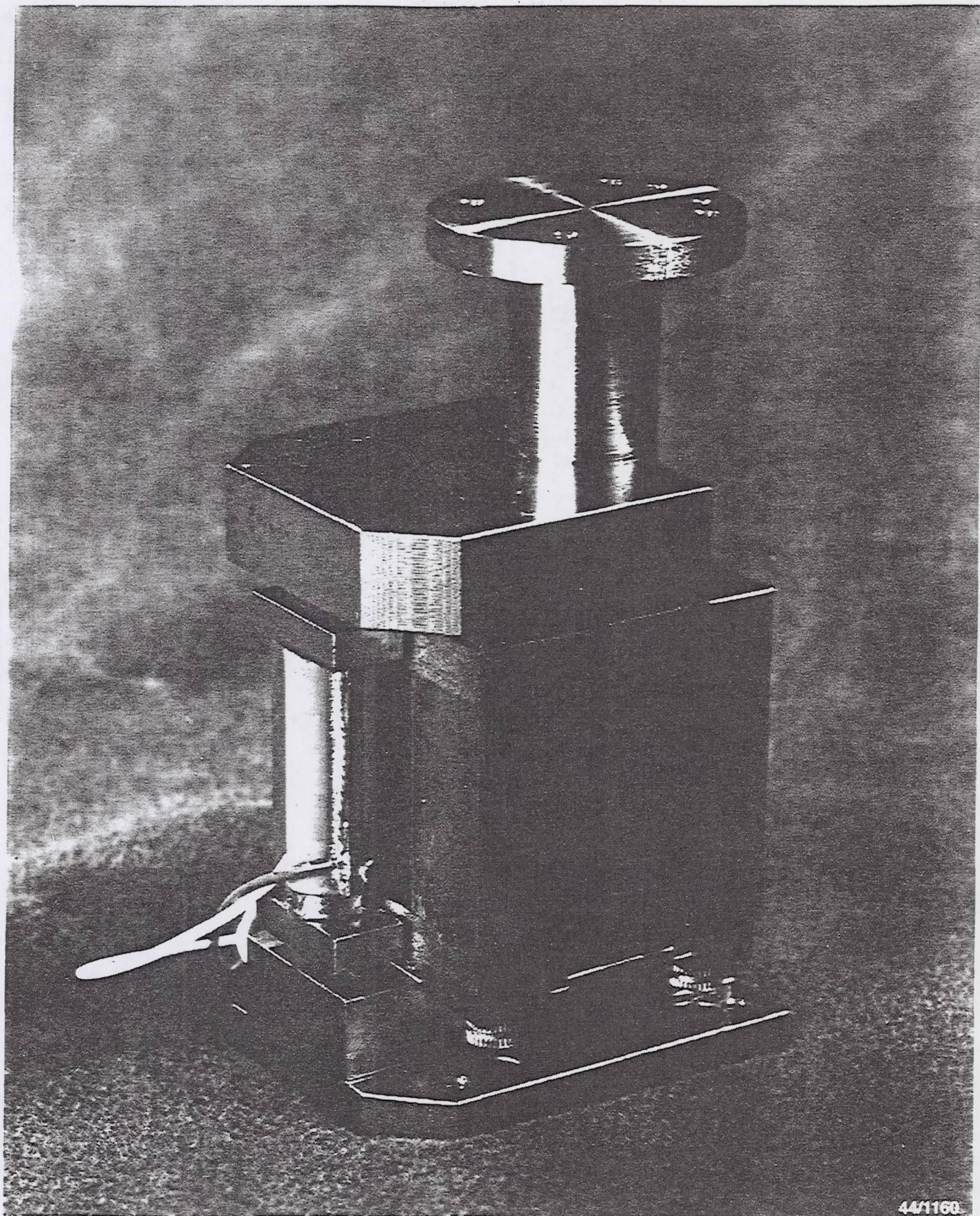


Active Stage Performance



- Motion-Amplified (4:1) PMN Ceramic Actuator
- 20 Hz. Response at 10-150V



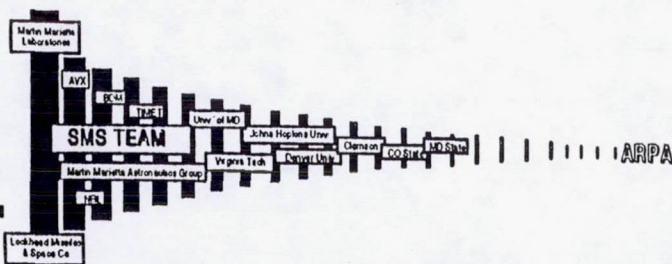


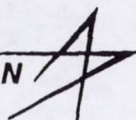
44/1160

Overview of Work Done

Technical Issues

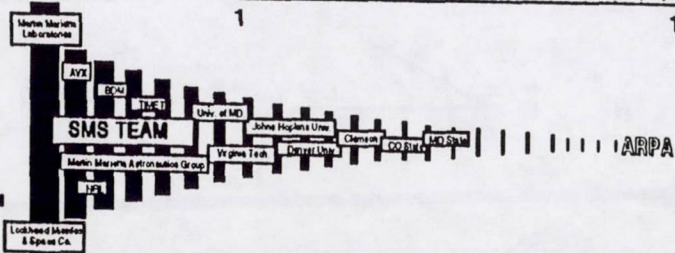
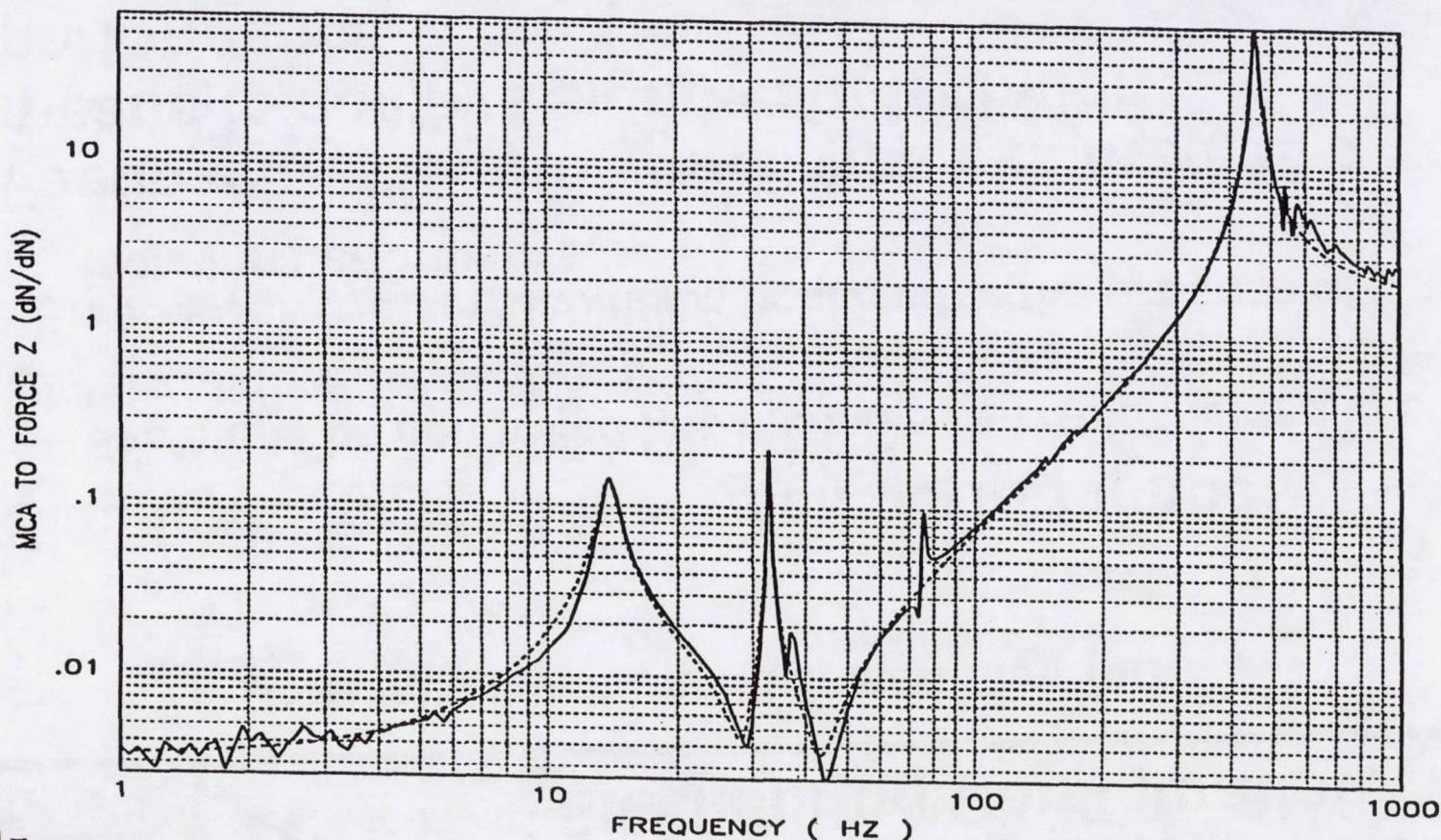
- **Anticipated:**
 - Drift in load cell limits performance at low frequencies
 - Dynamics coupling between axial and lateral motions
 - Significant nonlinearities in SMA springs
 - Lack of sufficient stroke in MCA actuator
- **Not anticipated:**
 - MCA to force transfer function “biased” at low frequencies





Modeling and Control Synthesis: SMA Spring Configuration

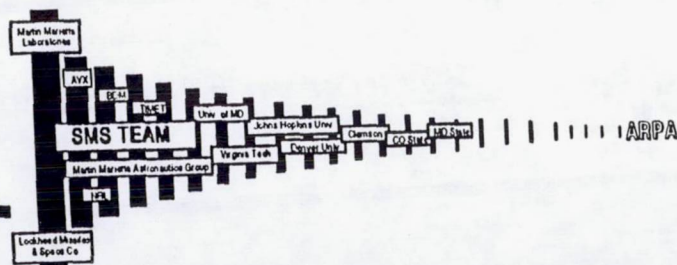
Control Design Model: MCA Voltage to Payload Axial Force

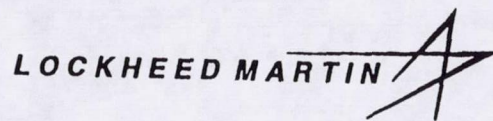


Modeling and Control Synthesis: Steel Spring Configuration

Consequence of Unanticipated Bias Term

- **Bias limits control feedback performance**
 - System to be controlled has unstable zero (bias added to s^2 term at low frequencies).
 - Feedback system stability is achieved at the expense of isolation performance.
- **Feedback + “feedforward” was explored as a means to achieve significant isolation performance.**

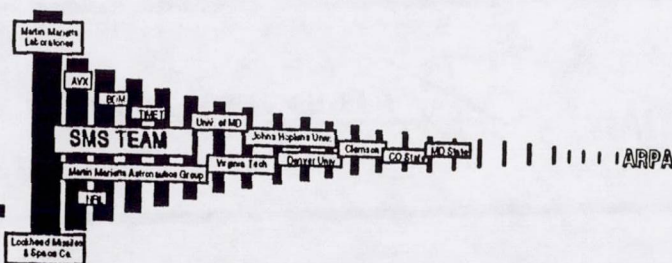




Modeling and Control Synthesis: SMA Spring Configuration

Still Bias Term in MCA Voltage to Axial Force

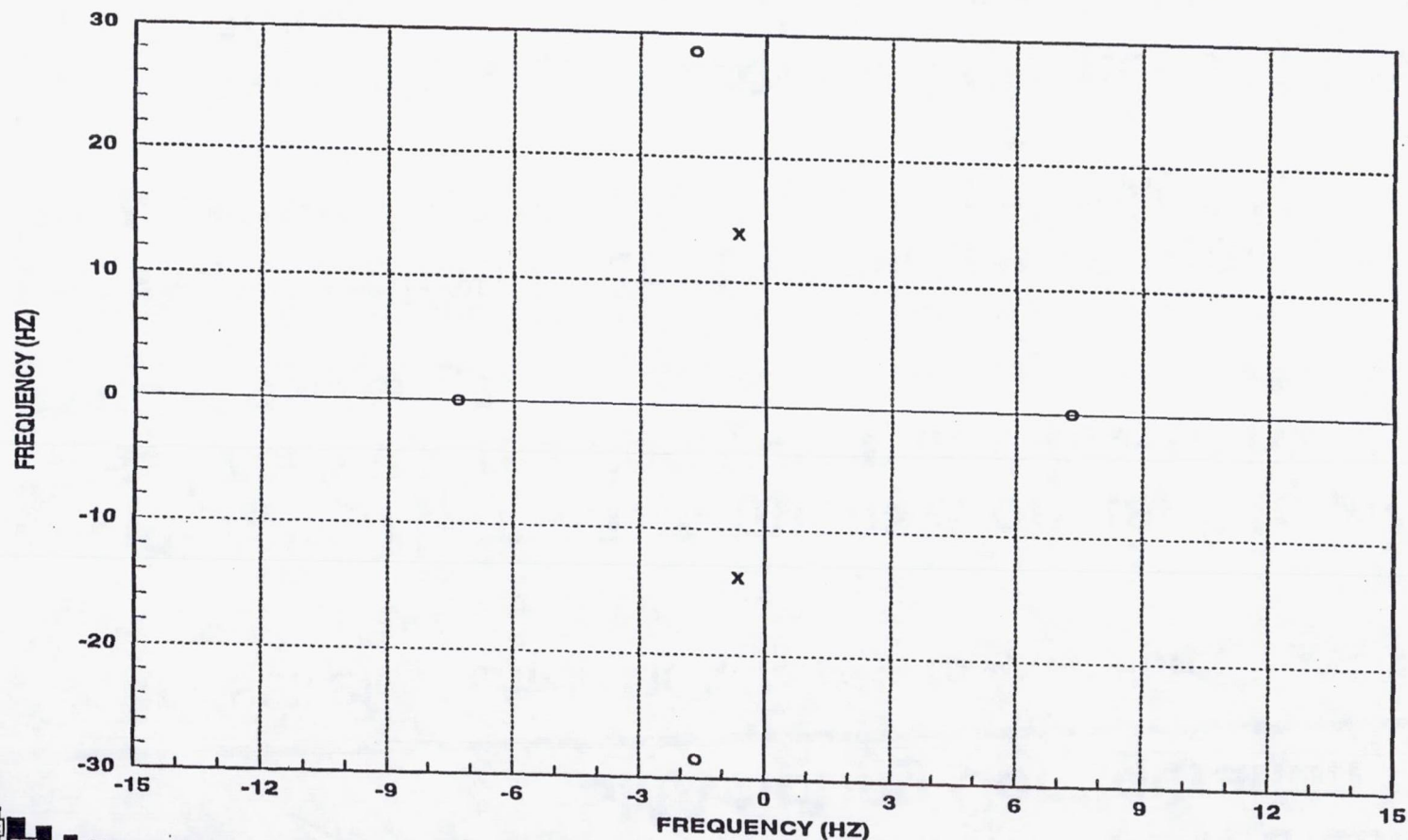
- Feedthrough term in compensation used to move “bias” zero up imaginary axis in the 1-10 Hz frequency range.
- Less uncertainty in control synthesis process because system is well modeled above 1 Hz.
- Stabilization does not require high gains at low frequencies.



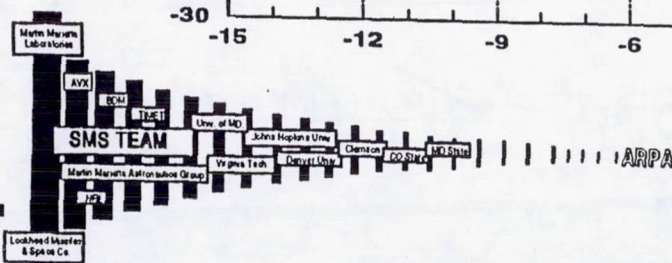


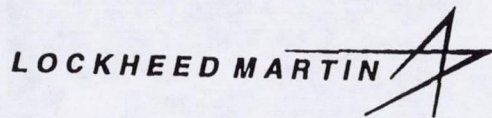
Modeling and Control Synthesis: SMA Spring Configuration

Pole-Zero Pattern for Control Design Model



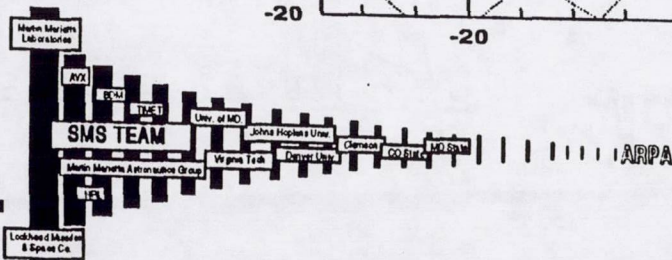
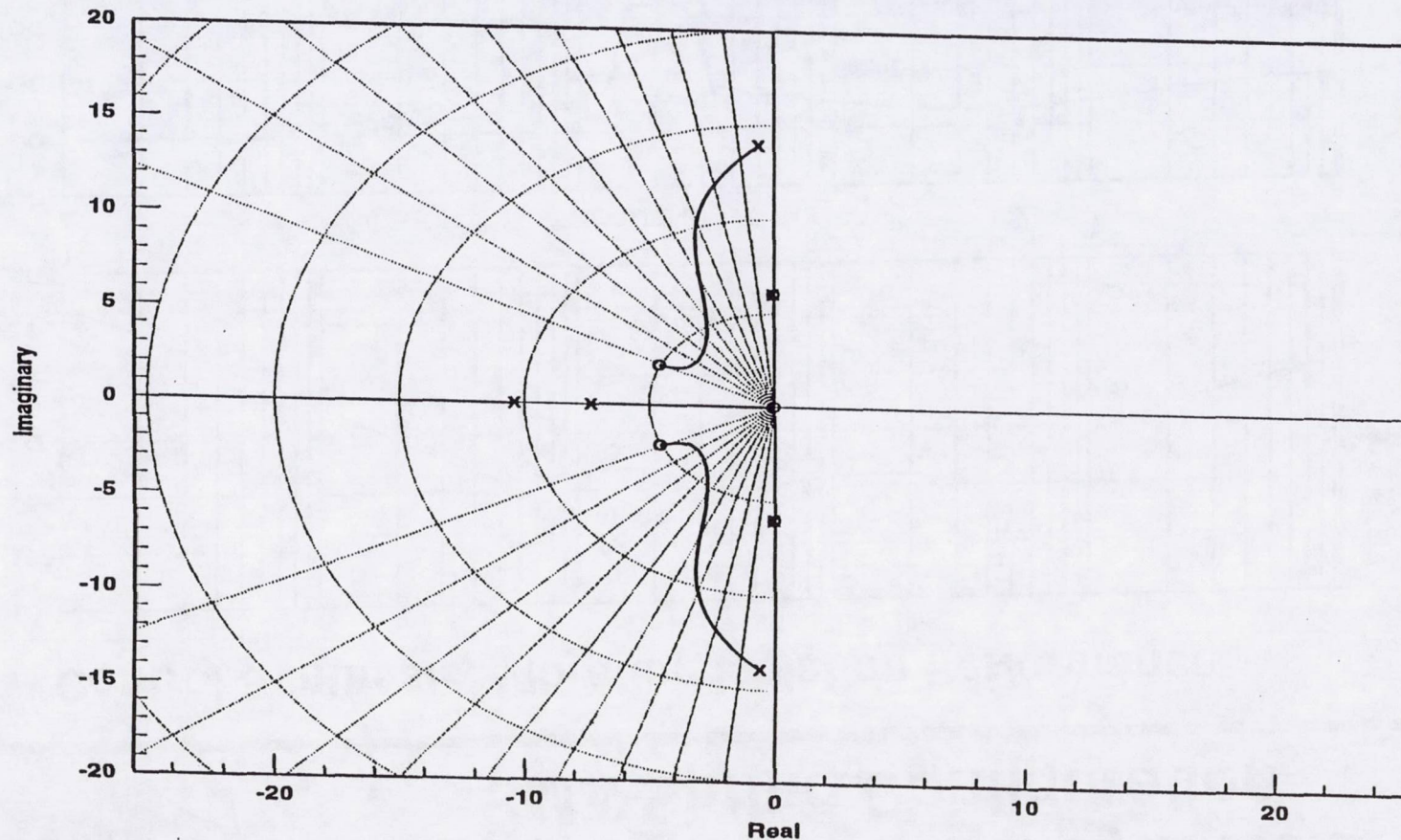
270





Modeling and Control Synthesis: SMA Spring Configuration

Control Synthesis: Pole-Zero Configuration for Compensator

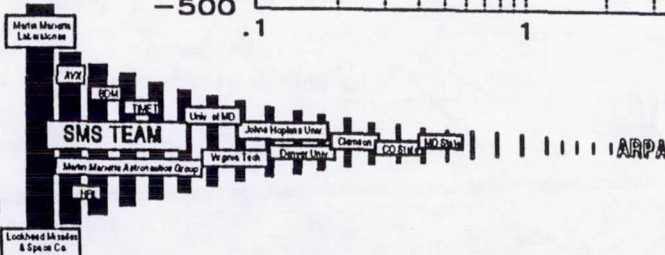
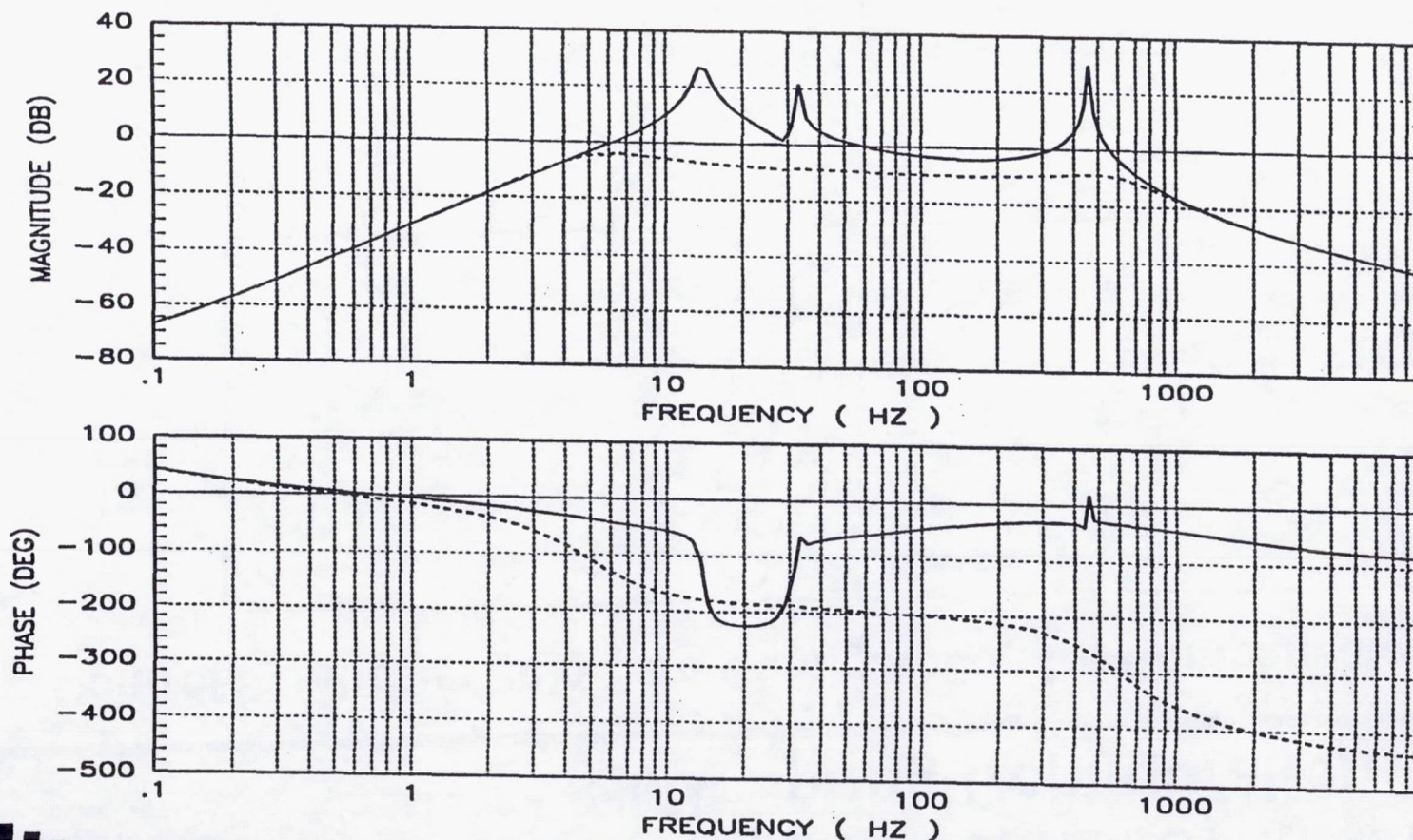


SMS Team Proprietary Information

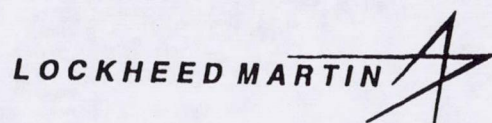


Modeling and Control Synthesis: SMA Spring Configuration

Control Synthesis: Vibration Isolation Performance

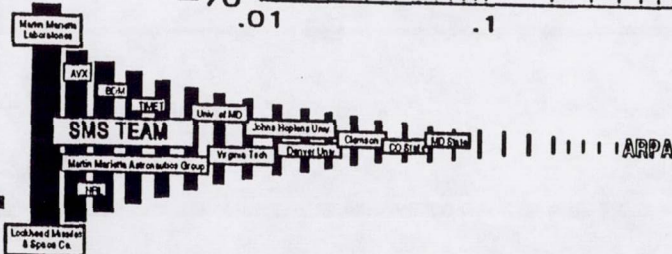
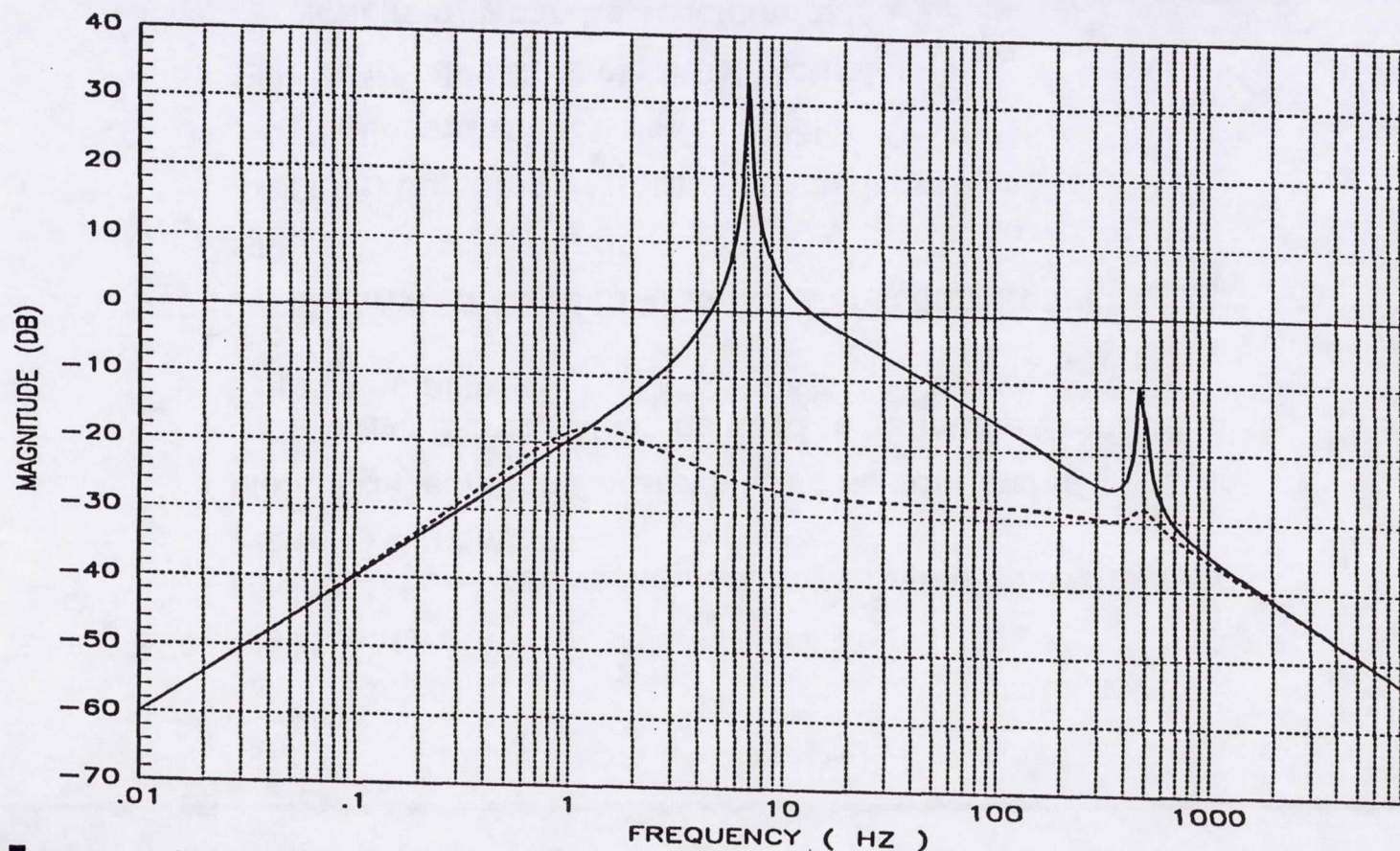


SMS Team Proprietary Information



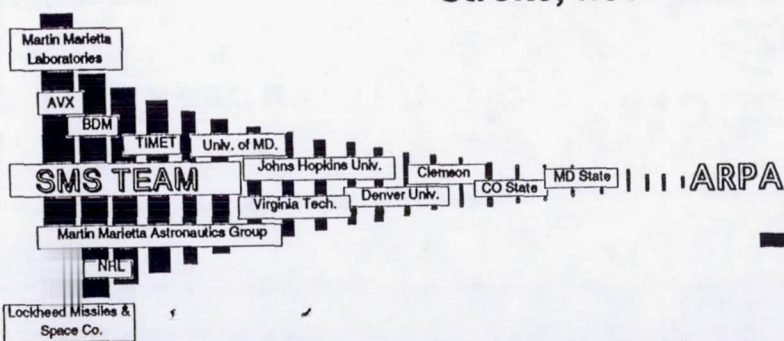
Modeling and Control Synthesis: Steel Spring Configuration

Control Synthesis: Vibration Isolation Performance



SMS Team Proprietary Information

- **Active Mounts**
 - Hybrid Active-Passive Mounts may provide insensitivity to Platform Dynamics
 - Multi-Axis Isolation/Control should be considered
 - Stiff Active Elements can be used to attenuate Broadband Transmissibility
- **Smart Materials applied to Vibration Canceling Mount**
 - Shape-Memory Springs
 - Good Damping Performance validated
 - Nonlinear Characteristics verified
 - Electrostrictive Ceramic Stack Actuators
 - Nonlinearity can be accommodated
 - Limited Stroke can be increased mechanically
 - Stroke, not Force Output, is primary limitation



omit THIS
PAGE

Smart Materials

Chairperson: Dr. Joycelyn Simpson

SONOPANEL™ 1-3 PIEZOCOMPOSITE PANELS
FOR ACTIVE SURFACE CONTROL

R. Gentilman, L. Bowen, D. Fiore, H. Pham, and W. Serwatka

Materials Systems Inc.
521 Great Road
Littleton, MA 01460

508-486-0404
Fax: 508-486-0706
e-mail:<76035.1644@compuserve.com>

Materials Systems Inc. has developed a cost-effective technology for producing 1-3 piezoelectric ceramic/polymer composites for use in active surface control. The advantages of 1-3 piezocomposites as both sensors and actuators have been recognized for many years, however viable manufacturing processes were not available until recently. MSI's 1-3 piezocomposite SonoPanel™ transducers consist of an array of piezoelectric ceramic rods arranged in a compliant polymer matrix. The standard SonoPanel™ composite consists of 15 volume percent PZT-5H rods 1.1 mm diameter x 6.3 mm long in a matrix of soft polyurethane. Stiff face plates are then bonded to the 1-3 composite sheet for stress amplification when used as a sensor and to enhance the surface response uniformity when used as an actuator. Many variations on this composite design have been produced for specific application requirements.

The key technology in SonoPanel™ manufacturing is MSI's PZT ceramic injection molding process. Using this process, an entire array of piezoelectric ceramic rods can be molded in one operation using specially designed tooling. The process eliminates the need for handling thousands of individual PZT rods during composite manufacturing. Injection molded PZT preforms can be formed at a rate of one per minute. Several thousand components with excellent piezoelectric properties and part-to-part reproducibility have been manufactured to date.

MSI's piezocomposite fabrication process has been successfully scaled up for low volume manufacturing. More than thirty 0.25 x 0.25 meter SonoPanel™ transducers have been produced and evaluated under an ONR manufacturing demonstration program. The transducers have been tested

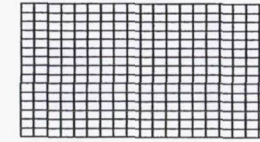
by the Naval Research Laboratory and show high receiving voltage sensitivity and transmitting voltage response as well as symmetrical beam patterns.

Next generation SonoPanel™ transducers, with materials and designs optimized for Navy systems, are under development as part of a new ARPA smart materials program. Advanced panels for active surface control are being developed by incorporating actuators, pressure sensors, and velocity sensors – all made from 1-3 composite materials – into an autonomous smart panel. Various feedback strategies can be employed to control the external panel surface to zero velocity or to a predetermined velocity or impedance.

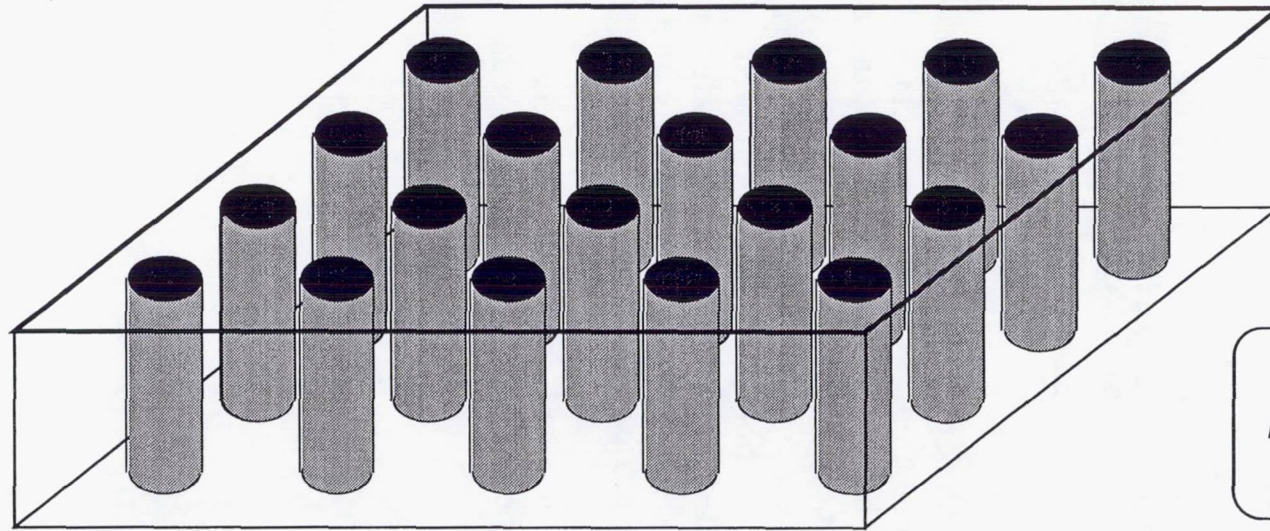
MSI's ceramics injection molding technology has also been used to produce net shape components for other applications. One new application being pursued is the production of a net-shape 2-2 bender array as the active component in a high displacement, low frequency air-acoustic sound source. Another potential application under consideration is complex-shape PZT actuators, such as curved, ribbed, and/or corrugated plates. These complex shape injection molded components can be conformed to curved surfaces and offer anisotropic actuation capabilities – for the same production cost as simple, flat piezoelectric patches.

Contractual support for this work from the Office of Naval Research and the Advanced Research Projects Agency is gratefully acknowledged.

1-3 Piezoelectric Composite



Materials
Systems
Inc.

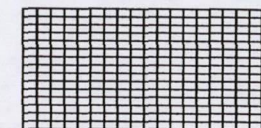


*PZT rods
in Polymer
matrix*

278

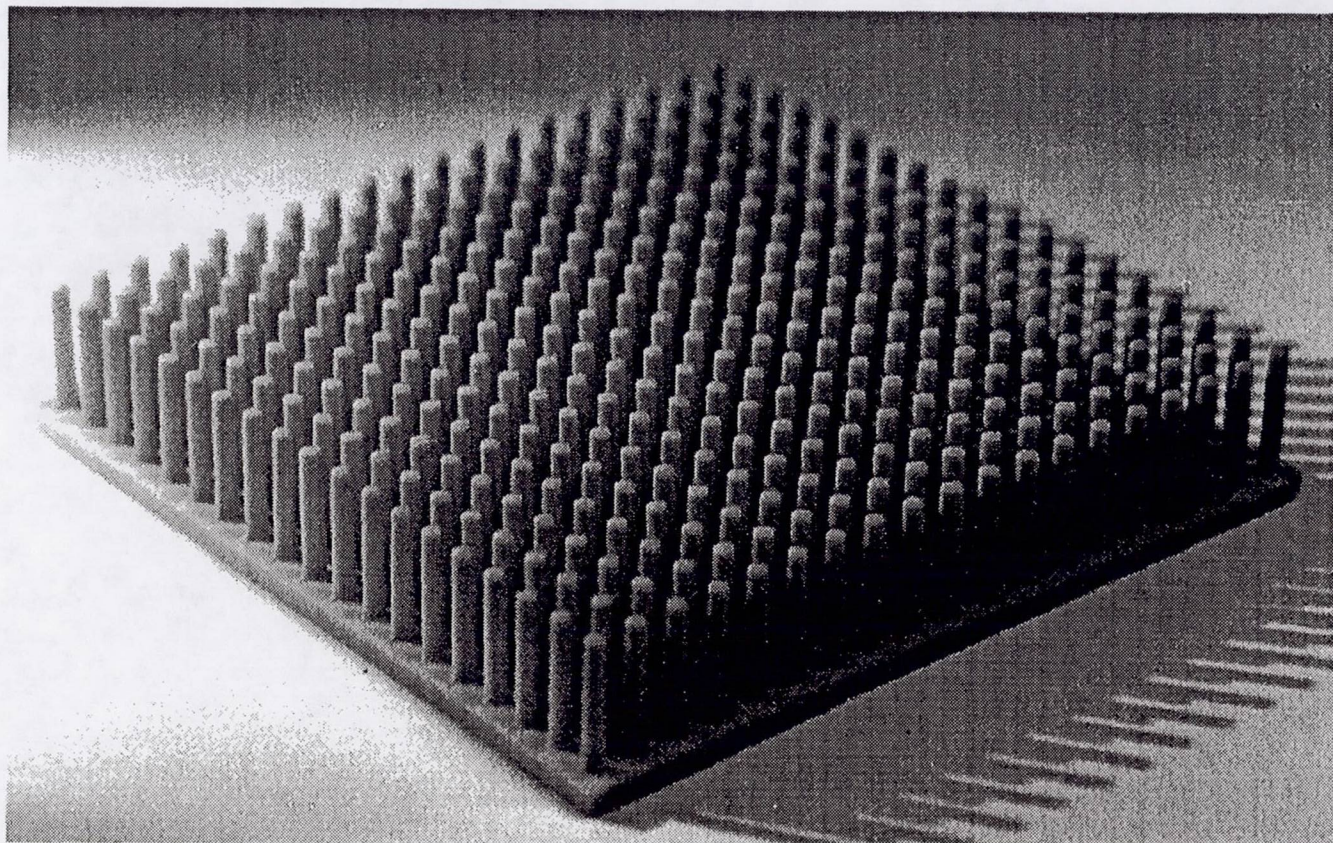
Advantages:

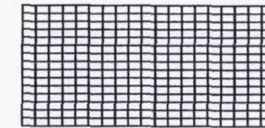
- High receive and transmit sensitivity
- Lateral d_{31} effects minimized
- Highly directional response
- Low density – low acoustic impedance
- Electrical impedance matched
- Conformable
- Low cost



Materials
Systems
Inc.

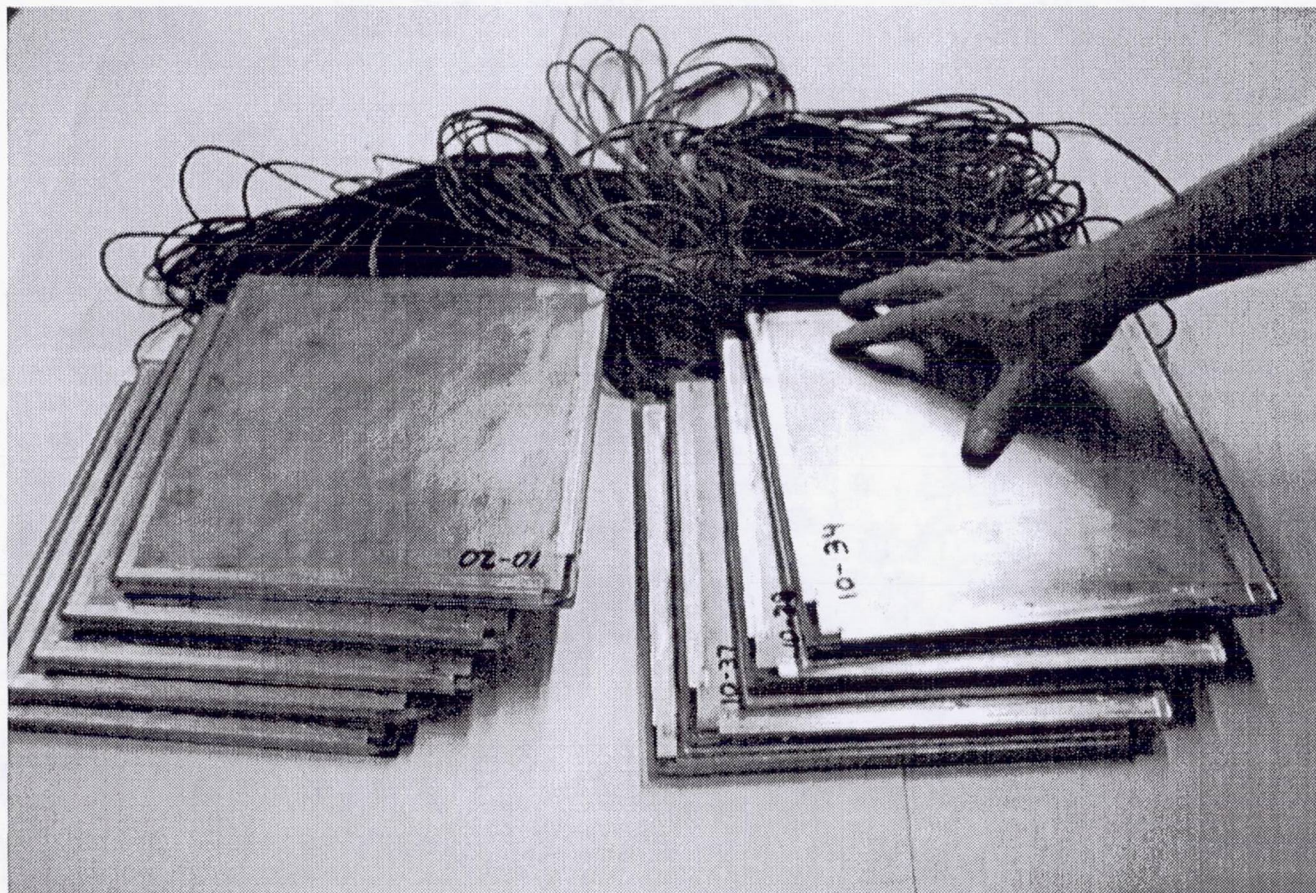
INJECTION MOLDED NET SHAPE PZT PREFORM





Materials
Systems
Inc.

FINISHED SONOPANEL™ TRANSDUCERS



Processing of Fine-Scale Piezoelectric Ceramic/Polymer Composites for Sensors and Actuators

V. F. Janas and A. Safari

Department of Ceramic Engineering and Center for Ceramic Research, Rutgers University, Piscataway, NJ 08855-0909, USA

*This work supported by the Office of Naval Research

INTRODUCTION

In the past decade, piezoelectric ceramic/polymer composites have been used in transducers for a variety of applications. These applications include hydrophones, biomedical imaging, non-destructive testing, and air imaging. Recently, much attention has been given to processing methods for forming large area composites, or multifunctional smart ceramic/polymer composites for advanced applications. Large area composites may find use as vibrational dampers, while smart ceramic/polymer composites will find applications in smart structures and systems. In this review, methods for processing both large area and multifunctional ceramic/polymer composites for acoustic transducers were discussed. Forming methods addressed included: tape casting, fiber processing, lost mold, honeycomb dicing, and the relic process. The current capabilities, strengths, and limitations of each method were reviewed. Several of the methods have demonstrated composites with extremely fine-scale ceramic phases ($< 50 \mu\text{m}$).

OBJECTIVE

The objective of the research effort at Rutgers is the development of lead zirconate titanate (PZT) ceramic/polymer composites with different designs for the above mentioned applications.

PIEZOELECTRIC COMPOSITES

A composite is an integration of a ceramic and a polymer in a configuration that utilizes the attributes of both phases. Some properties of the composite may exceed those of the single phase materials. In addition, the properties of the composite material may be tailored by changing the constituent phases or their configuration (or connectivity).

The advantages of piezoelectric ceramic/polymer composites include: low density ρ for good acoustic impedance matching to the coupling media, low dielectric constant K resulting in excellent voltage coefficients g_{33} , g_h , high piezoelectric figures of merit $d_{33}g_{33}$ and $d_h g_h$, and flexibility to conform to curved surfaces.

CURRENT PROJECTS

Several of the ongoing projects at Rutgers University on piezoelectric ceramic/polymer composites are listed in Figure 1. The projects include: novel composite designs using ceramic tapes, forming of PZT yarn and its inclusion into composites, a modified lost mold method, dicing of honeycomb composites, and woven composites formed via the relic process. The highlights of each method are discussed in the following paragraphs.

In the tape casting work, novel composite designs are being developed using thinly cast ceramic sheets. Composites with 2-2, 2-0-2, and 1-3 connectivity have been demonstrated. Ceramic scale as fine as 20 μm were shown, as were composites with multiple ceramic phases. Multiple ceramic phases can be used to further tune the composite properties. Composites with a gradient in active phase volume fraction, shown in Figure 2, have a gradient in their piezoelectric coefficient.

The PZT yarn work has developed a process to form continuous PZT fibers and incorporated them into composites with unique architectures via traditional textile methods such as weaving, knitting, and braiding. The Viscous Suspension Spinning Process (VSSP) from Advanced Cerametrics Incorporated was shown, as were typical 10 μm PZT fibers formed using the process. These fibers have been collected in the form of yarn, and sized to increase their strength for downstream processing. The fibers were sewn through a ceramic honeycomb support structure, and formed into a composite. The composite contains a unique "composite in a composite" microstructure. By using the VSSP process to form other active ceramics, a multifunctional ceramic/polymer composite is readily formed.

A modified lost mold method demonstrated fine-scale, large area composites using both punched plastic molds and hollow plastic fibers. Ceramic poles with 70 μm diameters were shown.

Composites using a honeycomb ceramic phase were presented. In this work, the phase connectivity and shape were modified by dicing the ceramic perpendicular to the extrusion direction. Changing the connectivity from 3-1 to 1-3 increased the hydrostatic response of the composite. Ceramic phase cross-sectional shape did not effect piezoelectric properties.

Finally, in the relic process, fine-scale, large area composites with novel architectures were demonstrated. An overview of the relic process was presented, and the structure and properties of shell composites (Figure 3) were shown.

SUMMARY

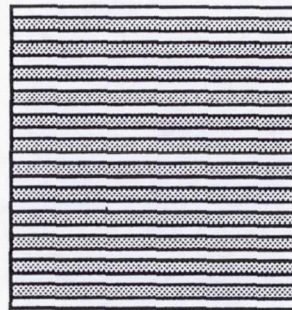
A number of novel methods for processing both large area and multifunctional ceramic/polymer composites for transducers were discussed. The capabilities, strengths, and limitations of each method were reviewed. The variety of forming methods serves as a tool kit for forming optimal composite architectures for a variety of applications.

PROJECTS

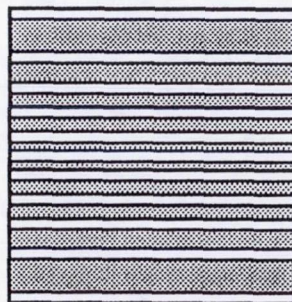
- **Engineering of Novel Composite Designs Using Thin Tapes**
- **Formation of PZT Fibers via VSSP, and Incorporation of the Fibers into Piezoelectric Fiber/Polymer Composites**
- **Fabrication of Fine-Scale, Large Area 1-3 PZT/Polymer Composites Using a Modified Lost Mold Method**
- **Effect of Ceramic Phase Connectivity on Composite Electromechanical Properties**
- **Development of Piezoelectric Ceramic/Polymer Composites with Different Fiber Architectures Using the Relic Process**

FIGURE 2

COMPOSITES WITH CERAMIC VOLUME FRACTION GRADIENT

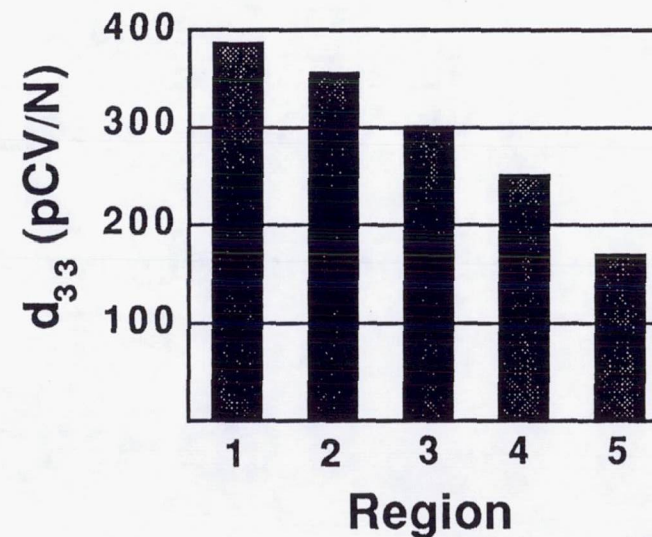


2-2



Gradient 2-2

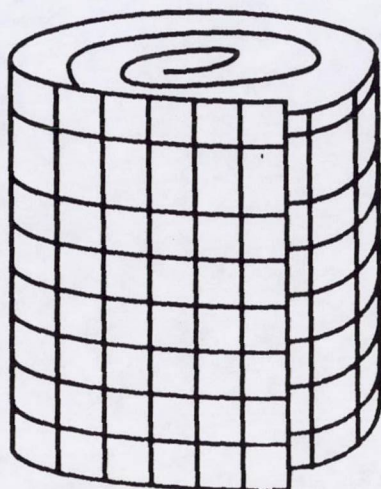
d_{33} versus Region in Volume Fraction Gradient composites



THE RELIC PROCESS

Shell Structure

Effect of Wrapping Tightness and Soak Order on the Properties of Shell Composites (in Eccogel-45). Average of five Specimens.



PROPERTY	LOOSE MNS	LOOSE SNM	TIGHT SNM
Density (g/cc)	3.7	3.3	3.7
Volume % PZT	39	33	39
K	200	175	200
$\tan \delta$ (%)	3.5	5.1	5.5
d_{33} (pC/N)	300	230	290
g_{33} (mVm/N)	170	150	160
d_h (pC/N)	90	60	100
g_h (mVm/N)	50	40	60
$d_h g_h$ (fm /N)	4500	2400	6000
k_t	0.30	0.26	0.28
k_p	0.19	0.20	0.19

Page intentionally left blank

519-27
NB2047
61462
035105
1 p.

**RAINBOWS and CERAMBOWS: The Technologies of
Pre-Stressed Piezo Actuators**

Gene H. Haertling
Clemson University
Clemson, SC 29634-0907, USA

Amplified mechanical displacement effects, similar to those observed in the recently reported Rainbow actuators, have also been found to exist in pre-stressed ceramic/metal composite structures coined as CERAMBOWs - an acronym for CERamic And Metal Biased Oxide Wafer. Mimicking the Rainbows in many ways, the intentionally created internal compressive and tensile stresses within the Cerambows are used to amplify their displacement properties via the combined effects of piezoelectric d31 strain and domain re-orientation. They are fabricated from ferroelectric, piezoelectric or electrostrictive materials and metal substrates of significantly different thermal expansions which are largely responsible for the creation of the stress. Typical ceramics used in Cerambows are PZT, PLZT, PBZT, PSZT and PMN and some typical metal substrates are Al, Ag, Ni, brass, steel and Be/Cu foil. Shapes can vary from round disks to square plates and rectangular bars. Formed at an elevated temperature of approximately 250°C, the stresses on cooling to room temperature are generally sufficient to produce displacements as large as 0.125mm (5 mils) when activated unipolar and 0.25mm (10 mils) when operated bipolar at 450 volts in a dome mode. Comparing equal structures of a Cerambow with a Rainbow, the Cerambow was found to achieve approximately 70% of the displacement that would normally be obtained with a Rainbow. Although this difference in displacement is sufficient to prefer a Rainbow for many applications, there are some advantages for the Cerambow. Among these are (1) the processing temperatures are lower, (2) high lead-containing ceramics are not required and (3) in some instances the metal substrate is more convenient to interface with other elements of a device. However, the disadvantages include (1) lower displacement in the dome mode of operation, (2) the higher displacement saddle mode has not yet been demonstrated with a Cerambow and (3) the ceramic/metal bond interface is a possible failure area when operated for extended periods of time. The applications for Cerambows are considered to be similar to Rainbows, i.e., actuators, pumps, deflectors, vibrators, speakers, hydrophones, hydroprojectors, switches, etc.

520-27
ABS. ONLY
61466
235106
1 P.

Piezoelectric Actuator/Sensor Technology at Rockwell

Ratnakar R. Neurgaonkar
Rockwell International Science Center
Thousand Oaks, CA 91360

We describe the state-of-the art of piezoelectric materials based on perovskite and tungsten bronze families for sensor, actuator and smart structure applications. The microstructural defects in these materials have been eliminated to a large extent and the resulting materials exhibit exceedingly high performance for various applications. The performance of Rockwell actuators/sensors is at least 3 times better than commercially available products. These high performance actuators are being incorporated into various applications including, DoD, NASA and commercial. The multilayer actuator stacks fabricated from our piezoceramics are advantageous for sensing and high capacitance applications. In this presentation, we will describe the use of our high performance piezo-ceramics for actuators and sensors, including multilayer stacks and composite structures.

521-27
61468

Functional and Multifunctional Polymers: Materials for Smart Structures.

S. Arnold, L.M. Pratt, J. Li, M. Wuagaman and I.M. Khan*

Department of Chemistry

Clark Atlanta University

Atlanta, GA 30314

235107
6 p.

The ultimate goal of the research in smart structures and smart materials is the development of a new generation of products/devices which will perform better than products/devices built from passive materials. Most of the current studies in the area is focussed on developing and understanding smart structures which are really a engineered packaging of a collection of sensors, actuators and the controller unit. Also, presently most of the active materials utilized in such devices are inorganic materials. There are, however, a few examples of multilayer polymer systems which function as smart structures e.g. a synthetic muscles which is a multilayer assembly of a poly(ethylene) layer, a gold layer and a poly(pyrrole) layer immersed in a liquid electrolyte. Oxidation and reductions of the active pyrrole layer causes the assembly to reversibly deflect and mimic biological muscles. The drawback of such as a setup is slow response times and the use of a liquid electrolyte. Multifunctional polymers have been developed by us which will eliminate the use of a liquid electrolyte, and also because the functionalities of the polymers are within a few hundred angstroms, an improved response times to changes in the external field should be possible. Such multifunctional polymers may be classified as the futuristic "*smart materials*". These materials are composed of a number of different functionalitites (e.g. sensors, actuators and controller unit) which work in a synergistic fashion to function as a device. The device performs on the application of an external field and such multifunctional polymers may be scientifically labeled as "*field responsive polymers*". Our group has undertaken a systematic approach to develop functional and multifunctional polymers capable of functioning as field responsive polymers (*see Slide*). These polymers have potential application as synthetic biomembranes, electrorheological materials, synthetic muscles, MEMS devices, microwave shields, sensors etc. Our approach to develop multifunctional polymers utilizes multicomponent polymer systems (block copolymers and graft copolymers), the strategy involves the preparation of block or graft copolymers where the functionalities are limited to different phases in a microphase separated system. Depending on the weight (or volume) fractions of each of the components, different microstructures are possible e.g. cylinders, spherical, lamellae. And, because of the intimate contact between the functional components an increase in the synergism between the functionalities may be observed. In this presentation three examples of multifunctional polymers developed in our laboratories will be reported.

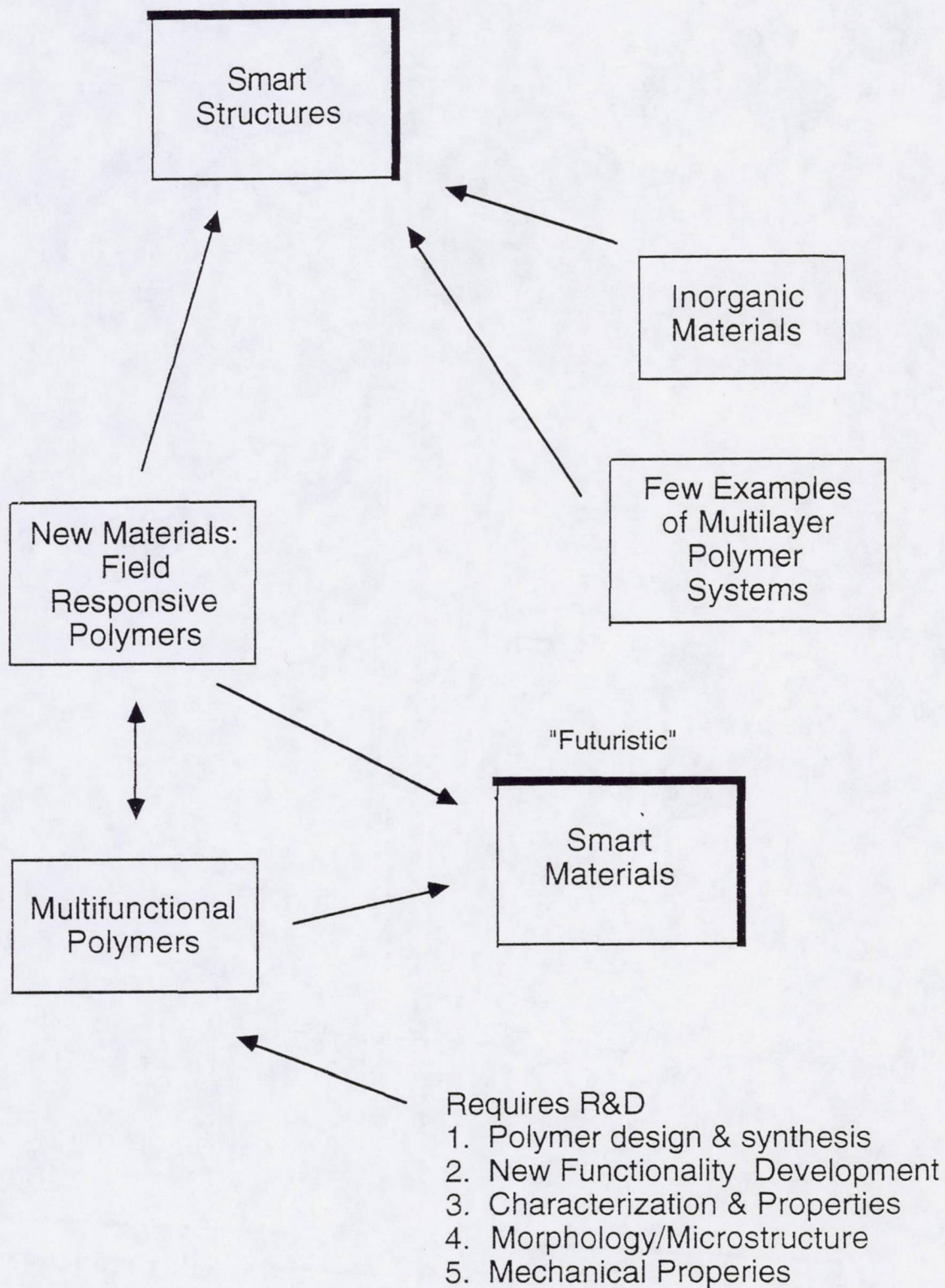
The first class of multifunctional polymers are the microphase separated mixed (ionic and electrnic) conducting or MIEC block copolymers. Such block copolymers may be generated by synthesizing a block copolymer containing an electronic and an ionic conducting block e.g. poly[(3-methylthiophene-co-3-octylthiophene)]-block-poly[ω -methoxyocta(oxyethylene) methacrylate] appropriately doped with FeCl_3 and LiClO_4 . These polymers exhibit both electronic and ionic conductivities, and are microphase separated (*see Slide*). Transmission electron microscopy (TEM) on some of the polymers

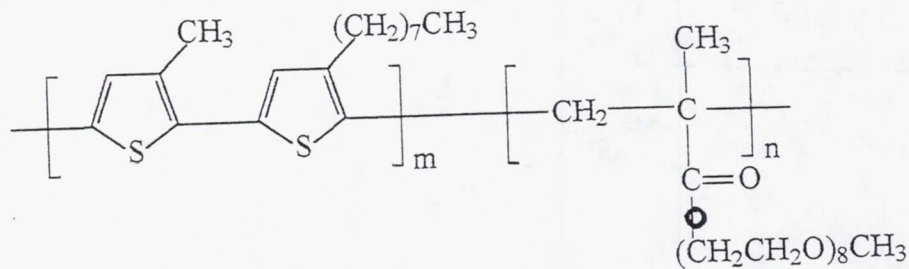
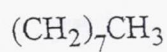
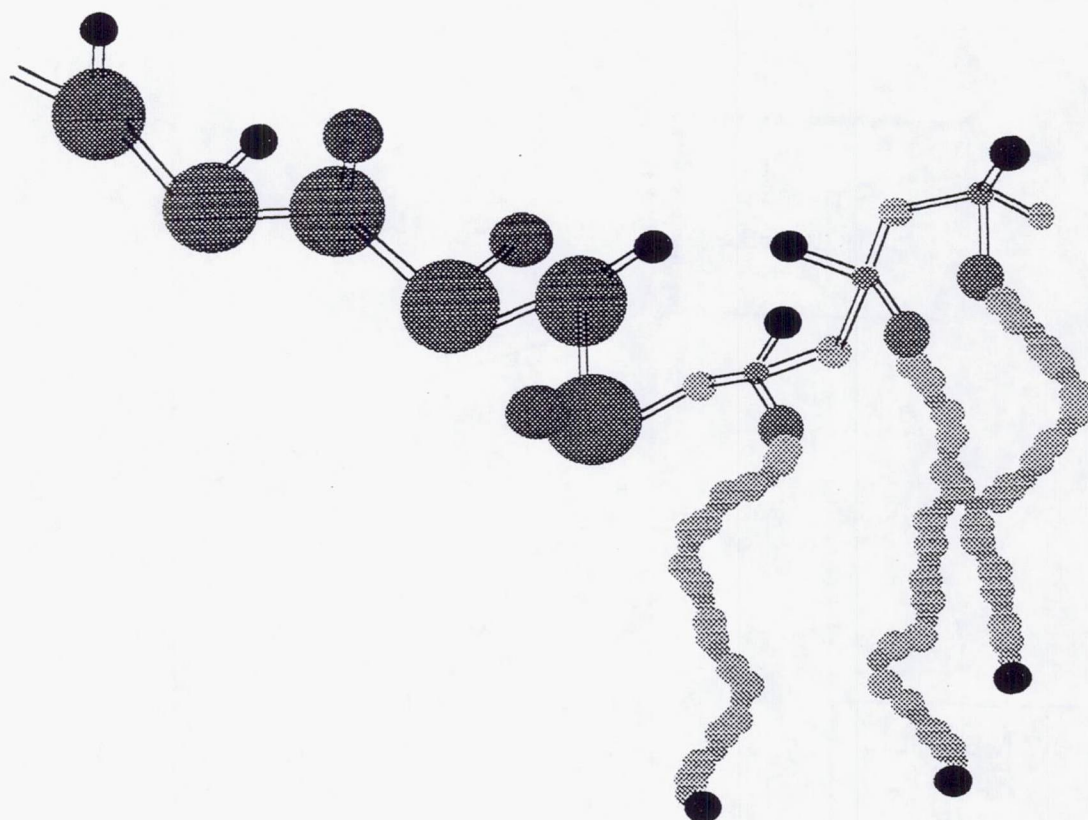
indicates that the microphases are approximately 300 to 600 angstroms of the lamellae type. This development represents a new concept in the area of multifunctional polymers and should permit the fabrications of all solid state MEMS devices. Furthermore, because the MIEC block copolymers are capable of transporting both electron and ions, it should be possible to fabricate biomembranes capable which mimic biological electron transfer processes.

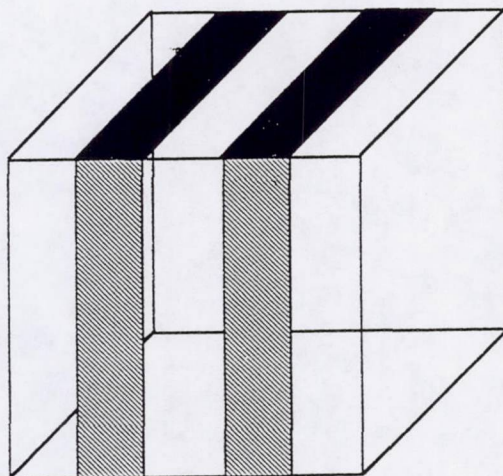
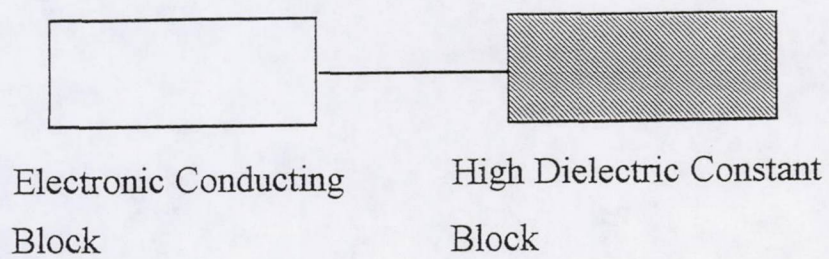
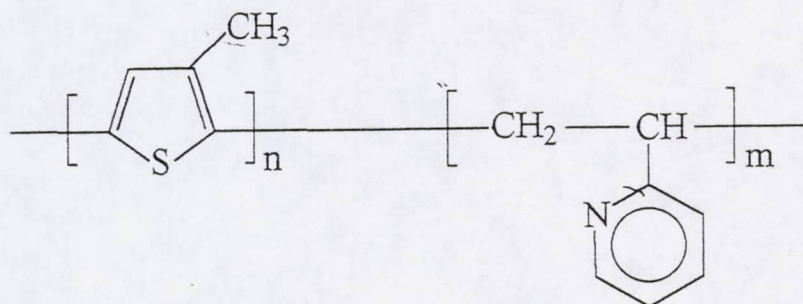
The second class of multifunctional polymers that are being developed in our laboratories are the biocompatible conductive materials and the conductive fluids. This is most rationally obtained by preparing poly(3-alkythiophene)s with oligo or poly(dimethylsiloxane) grafts. The dimethylsiloxane polymers are known to be biocompatible and is also a very low T_g (-123°C) material. By varying the weight fractions of the thiophene to the dimethylsiloxane content, brick hard to fluid like conductive materials may be prepared. Our immediate goal with these polymers are to evaluate the electroviscous properties of these polymers. The intention of the study is to correlate the molecular structure with the electrorheological properties.

The final class of multifunctional polymers may be considered microwave active smart polymers. The preparation of this class of multifunctional polymers, first required the development of functionality (high dielectric constant in the GHz range) in polymers which are observed in inorganic materials like barium titanate and ferrite. Potential applications of such new functional polymers are in shielding systems, dielectric resonator antennas, microwave transmission lines and waveguides. The functional high dielectric constant polymers have been developed by preparing molecular complexes of poly(2-vinylpyridine)/lithium perchlorate. The dielectric constants may be tuned by varying the lithium perchlorate content. Dielectric constants as high as 16.5 at 12 GHz has been observed. In order to prepare microwave active smart polymers i.e. in this case to vary the dielectric constant as a function of an electric field, poly(3-methylthiophene)-block-poly(2-vinylpyridine) block copolymers have been prepared. These block copolymers have been converted, through appropriate addition of LiClO_4 and FeCl_3 , to obtain a block copolymer with an electronic conductive block and an high dielectric constant block (*see Slide*). These block copolymers should be capable of responding to both electric fields and microwave frequencies. For example, a small current through the matrix may alter the nature of the ionic solvates/aggregates in the 2-vinylpyridine phase and a dynamic change in the dielectric constant may be possible. Applications of the high dielectric constant molecular composites and the block copolymers are in microwave shielding systems, dielectric resonator antennas microwave transmission line and waveguides.

We have in our laboratory a number of well characterized multifunctional polymers and over the next several months some preliminary studies are planned to evaluate the polymers as "smart materials", specifically as synthetic muscles, biomembranes and smart microwave shields. To develop the general area of "field responsive polymers" or "smart materials", the performance of smart devices must be evaluated and results carefully considered in the design of more desirable materials. This strategy will permit the development of the smart polymers and ultimately the availability of devices based on active materials.







Page intentionally left blank

522-26
ABS. only
61472

**Improved Damage Resistant Composite Materials Incorporating
Shape Memory Alloys**

235108

Jeffrey S. N. Paine
Paradigm, Inc., Blacksburg, VA, USA

1P.

Craig A. Rogers
Center for Intelligent Material Systems and Structures
Virginia Tech., Blacksburg, VA, USA

Metallic shape memory alloys (SMA) such as nitinol have unique shape recovery behavior and mechanical properties associated with a material phase change that have been used in a variety of sensing and actuation applications. Recent studies have shown that integrating nitinol-SMA actuators into composite materials increases the composite material's functionality. Hybrid composites of conventional graphite/epoxy or glass/epoxy and nitinol-SMA elements can perform functions in applications where monolithic composites perform inadequately. One such application is the use of hybrid composites to function both in load bearing and armor capacities. While monolithic composites with high strength-to-weight ratios function efficiently as load-bearing structures, because of their brittle nature, impact loading can cause significant catastrophic damage. Initial composite failure modes such as delamination and matrix cracking dissipate some impact energy, but when stress exceeds the composite's ultimate strength, fiber fracture and material perforation become dominant. One of the few methods that has been developed to reduce material perforation is hybridizing polymer matrix composites with tough kevlar or high modulus polyethynylene plies. The tough fibers increase the impact resistance and the stiffer and stronger graphite fibers carry the majority of the load. Similarly, by adding nitinol-SMA elements that absorb impact energy through the stress-induced martensitic phase transformation, the composites' impact perforation resistance can be greatly enhanced. The results of drop-weight and high velocity gas-gun impact testing of various composite materials will be presented. The results demonstrate that hybridizing composites with nitinol-SMA elements significantly increases perforation resistance compared to other traditional toughening elements. Inspection of the composite specimens at various stages of perforation by optical microscope illustrates the mechanisms by which perforation is initiated. Results suggest that the out-of-plane transverse shear properties of the composite and nitinol elements have a significant effect on the perforation resistance. Applications that can utilize the hybrid composites effectively will also be presented with the experimental studies.

Page intentionally left blank

OMIT THIS
PAGE

Fiber Optics

Chairperson: Leland Melvin

523-74
ABS. ONLY
61476

Fiber Optic Sensors for Smart Materials and Structures

H. Singh, C. C. Chang, T. Boyer, and J. S. Sirkis
Smart Materials and Structures Research Center
University of Maryland

235109

1P.

In this paper we describe recently developed fiber sensors which are capable of monitoring the health of smart-structures. The unobstrusive geometry of these sensors make them an excellent choice for embedding the sensor in composite materials to measure internal states of strain in structures and materials. Some of these sensors have gage lengths that can be tailored from tens of microns to many meters. We will describe various demodulation schemes (Pseudo-Heterodyne, Synthetic-Heterodyne, Homodyne, Differential-Cross Multiplier, and Single Channel Phase-Tracker) to obtain high bandwidth measurements, enabling measurement of static to high frequency impact generated strains with a dynamic response exceeding tens of thousands of microstrains. In addition, we will show that we can tailor the fiber sensor to either measure only strain and reject temperature response or measure only the temperature, or measure both temperature and strain simultaneously. We will also demonstrate the ability to measure multiple strain components inside a host simultaneously using a single fiber sensor embedded in the host using a certain sensor type and transverse strain immunity using another sensor type. Additionally we will show the ability to measure temperature up to 100°C using fiber optic sensors.

524-74
61480
6 P.
035110

High Temperature Testing with Sapphire Fiber White-Light Michelson Interferometers

A. Barnes, J. Pedrazzani, R. May, and K. Murphy,
Fiber & Electro-Optics Research Center, Virginia Tech
T. Tran, Fiber & Sensor Technologies
J. Coate, Wright Laboratory

Introduction

In the design of new aerospace materials, developmental testing is conducted to characterize the behavior of the material under severe environmental conditions of high stress, temperature, and vibration. But to test these materials under extreme conditions requires sensors that can perform in harsh environments. Current sensors can only monitor high temperature test samples using long throw instrumentation, but this is inherently less accurate than a surface mounted sensor, and provides no means for fabrication process monitoring. A promising alternative is the use of sapphire optical fiber sensors. Sapphire is an incredibly rugged material, being extremely hard (9 mhos), chemically inert, and having a melting temperature (over 2000 °C). Additionally, there is a extensive background of optical fiber sensors upon which to draw for sapphire sensor configurations.

White-Light Scanning Fiber Michelson Interferometry (WSFMI)

Sapphire optical fiber differs significantly from silica fiber in its waveguiding properties, the most significant aspect of which is that sapphire fibers have on the order of 100,000 propagation modes, while most silica fibers have only one. The huge number of modes creates a great deal of modal noise, which effectively spoils most interferometric sensing techniques. However, one interferometric technique that does work is white-light scanning fiber Michelson interferometry (WSFMI), for which the setup is depicted in the slide *White-Light Scanning Fiber Michelson Interferometer*. In this arrangement, a source with relatively low spatial coherence (here an LED) is injected into a singlemode fiber. This is passed through a 2x2 fiber coupler into a sensing arm and a reference arm. The sensing arm consists of a transmission fiber that leads back to the coupler, a reflector fiber, and a capillary tube in which the two fibers are aligned. Between the two fibers is a small air gap. It is this gap that the sensor measures, allowing it to monitor displacement, although such a displacement measurement can be configured to detect strain, temperature, or other test parameters. The reference arm consists of a GRIN lens which collimates the light coming out of the fiber, and a motorized actuator with a mirror mounted on it. The mirror is scanned back and forth, reflecting light back through the GRIN lens into the fiber. The light reflected from the sensing arm and reference arm are mixed together in the 2x2 coupler, and the signal is monitored with a photodetector. As the actuator moves, the optical path length of the reference arm changes. When the reference path length matches the sensor path length, constructive interference occurs, which is registered by the photodetector as a series of amplitude fringes. Constructive interference will occur at two points in the actuator's scan. This is shown for a WSFMI system using silica fiber in the slide *WSFMI Sensor Output - Sample 30 micron gap* (note here four fringe packets are observed, as the plot shows actuator translation forward and back). The first fringe packet will be when the path length matches that of the light reflecting off of the reflector fiber in the sensing arm. The second is when the path length matches that of the Fresnel reflections off of the end of the transmission fiber. By measuring the distance between the

two constructive interference fringe packets, the absolute gap size in the sensing arm can be determined.

Sapphire WSFMI

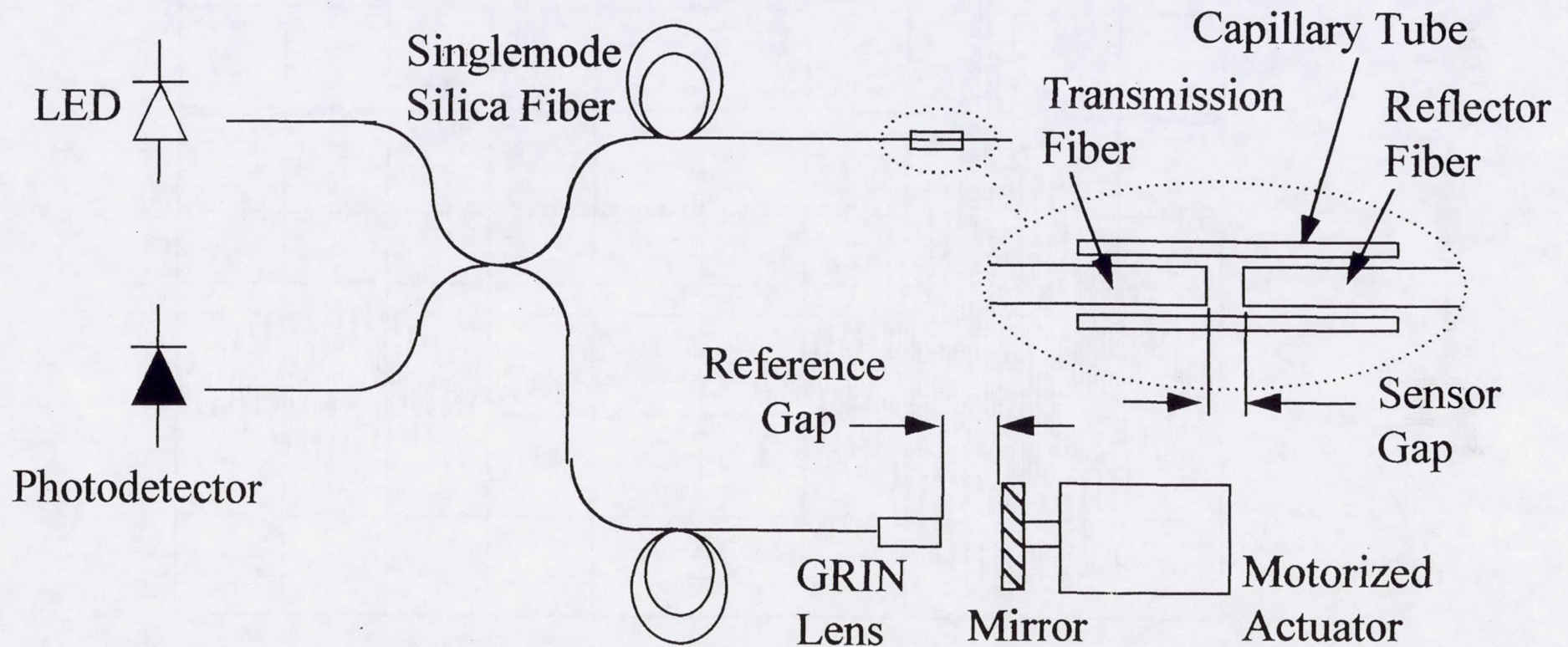
WSFMI can be used with sapphire fiber while other interferometric techniques cannot. This is because modal noise in interferometry causes different sets of amplitude fringes for different modes. These differing fringe packets interfere with each other, which makes it difficult to resolve single fringes. However, WSFMI only needs to look at the distance between two fringe packets, and not at individual fringes. The center of these fringe packets can be determined simply with an envelope detector. In this fashion, difficulties with modal noise can largely be avoided. Results using sapphire in a WSFMI system are shown in the slide *Sapphire WSFMI Sensor Output - Sample 30 micron gap*. It should be noted that the sapphire WSFMI plot is greatly compressed as compared to the silica plot. The lead peak in each fringe group for the sapphire plot corresponds to the entire fringe packet in the silica plot. The remaining fringes in the sapphire plot are due to modal noise. The lead peak can still clearly be discerned however. If the gap were to get much smaller though, the trailing fringes from the first fringe group would start to overlap the second fringe group, and the gap size could not be ascertained. This is a fairly minor concern, as the gap size can be chosen so that its expected range would not be too small.

Further tests with WSFMI have proved it to be a very linear sensor, for both silica and sapphire fiber systems. Its absolute measurement of gap size allows it to be used without lengthy calibration. Sensor measurements could be done at up to 50 Hz, over a 150 micron gap range. There is a trade off between frequency response and dynamic range, both of which were limited in these experiments by the actuator. These could be improved with a better actuator. Despite this, sapphire WSFMI has been demonstrated to be a viable sensor system for high temperature conditions.

Acknowledgments

Thanks to our sponsors NASA, Wright Laboratory at Wright-Patterson AFB, and Fiber & Sensor Technologies. Thanks also to Dr. Tianchu Li of the National Institute of Metrology, Beijing, China for his instrumental assistance with the WSFMI system.

White-Light Scanning Fiber Michelson Interferometer

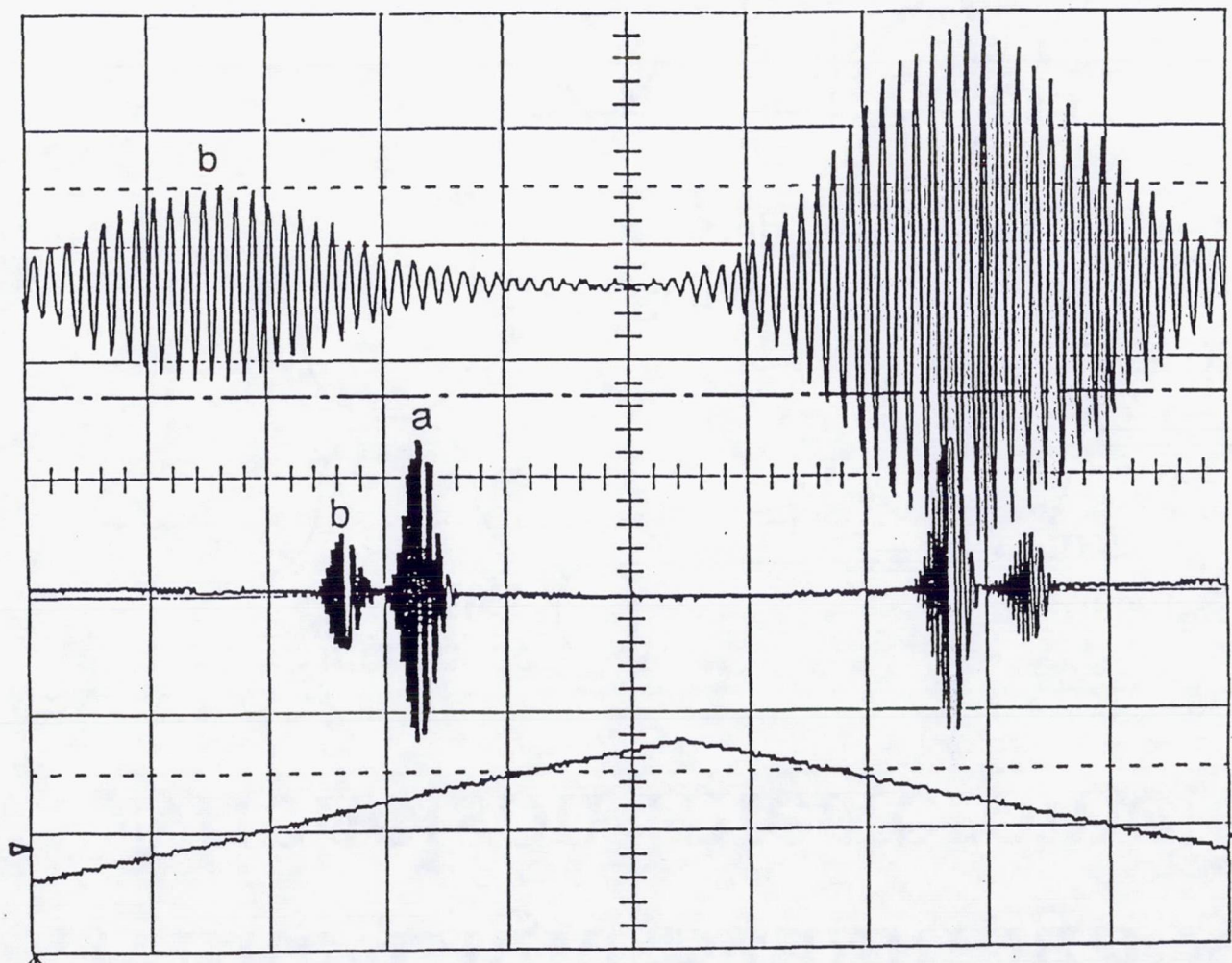


301



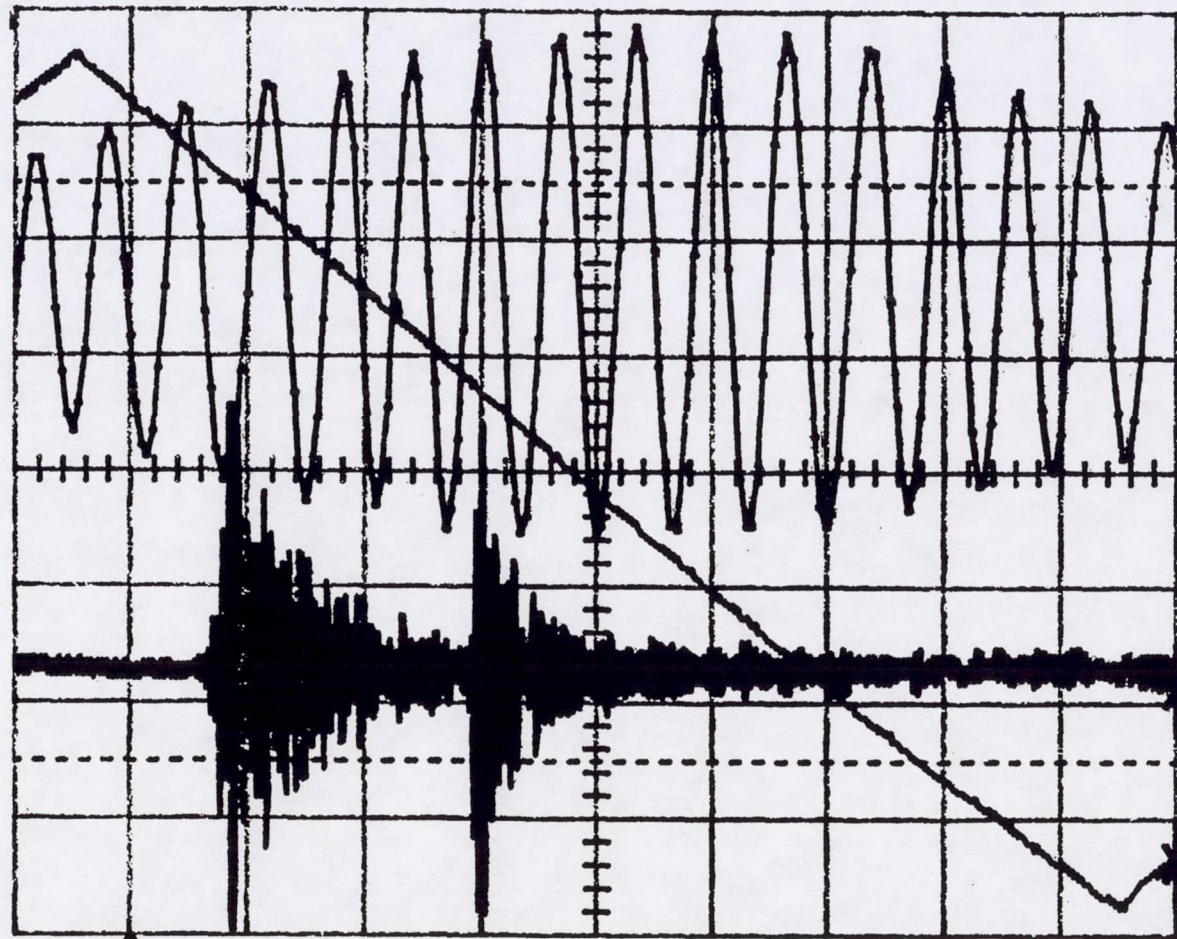
WSFMI Sensor Output

Sample 30 micron gap_a



Sapphire WSFMI Sensor Output

Sample 30 micron gap



Fiber & Electro-Optics
Research Center



Page intentionally left blank

555-74
ABS ONLY
61485

Metal-Coated Optical Fibers for High Temperature Applications

Jason Zeakes, Kent Murphy and Richard Claus
Fiber & Electro-Optics Research Center

235111

1 p.

Jonathan Greene and Tuan Tran
Fiber & Sensor Technologies, Inc.

A DC magnetron sputtering system has been used to actively coat optical fibers with hermetic metal coatings during the fiber draw process. Thin films of Inconel 625 have been deposited on optical fibers and annealed in air at 2000° F. Scanning electron microscopy and Auger electron microscopy have been used to investigate the morphology and composition of the films prior to and following thermal cycling. Issues to be addressed include film adhesion, other coating materials, and a discussion of additional applications for this novel technology.

**Digital Fringe Counting for Intrinsic
Fabry-Perot Interferometers**

Mark Froggatt and Leland Melvin
NASA Langley Research Center

526-74
APS-ONLY

61487

035113

1P

A digital dual-wavelength method of demodulating long (17cm) Intrinsic Fabry-Perot Interferometers (IFPI) is presented. The method builds upon previous techniques using small shifts in the lasing wavelength of a laser diode induced by changes in the driving current. The intensity of the light reflected from the IFPI is sampled at two carefully selected values of laser diode drive current. Digital logic is then used to count fringes based upon these two sampled values. Experimental verification of the method is described.

Key Words: intrinsic Fabry-Perot interferometer, fringe counting, strain sensor

*omit THIS
PAGE*

Applications and Modeling of Smart Materials

Chairperson: Robin Hardy

Page intentionally left blank

57-24
61489
2351140
6 P.

Layerwise Mechanics and Finite Elements for Smart Composite Structures with Piezoelectric Actuators and Sensors

Dimitris A. Saravanos¹, Paul R. Heyliger², and Dale A. Hopkins
NASA Lewis Research Center
Structural Mechanics Branch
21000 Brookpark Rd., MS 49-8
Cleveland, Ohio 44135

Abstract

Recent developments on layerwise mechanics for the analysis of composite laminates and structures with piezoelectric actuators and sensors are reviewed. The mechanics implement layerwise representations of displacements and electric potential, and can model both the global and local electromechanical response of smart composite structures. The corresponding finite-element implementations for the static and dynamic analysis of smart piezoelectric composite structures are also summarized. Select application illustrate the accuracy, robustness and capability of the developed mechanics to capture the global and local dynamic response of thin and/or thick laminated piezoelectric plates.

Introduction

The paper reviews some recent work in mechanics and finite elements for the analysis of smart composite structures (beams, plates and shells) with embedded piezoelectric actuators and sensors conducted in NASA-Lewis Research Center. Contrary to many reported approximate theories which attempt to replicate the induced strain or electric fields generated by a piezoelectric solid under an external electric field or applied load, the present approaches can represent the strong interlaminar inhomogeneity and the highly localized strains in piezoelectric composite laminates. Hence, the method has the capability to accurately model either the global or the local response of piezoelectric composite structures and can handle sections of high thickness. The mechanics have been developed from the coupled constitutive equations of piezoelectricity and Hamilton's variational principle of electric enthalpy, hence, the piezoelectric effect and resultant electromechanical coupling are accounted at the material level. In addition, beam, plate and curvilinear shell finite elements have been developed for the analysis of smart composite structures and the basic features of the approach are summarized for the case of smart laminated plate structures. Select evaluations demonstrate the capabilities and robustness of the developed methods in modelling typical structures under static and dynamic conditions.

Method

Some important points of the mechanics are summarized here. Additional details and evaluations may be found in refs. [1-3]. The coupled constitutive equations of the piezoelectric material are the starting point of the method:

¹ Senior Research Associate, Ohio Aerospace Institute.
To whom correspondence should be addressed at the above address; tel. (216) 433-8466, fax (216) 433-8011, e-mail: dsaravanos@lerc.nasa.gov

² Associate Professor, Civil Engineering Dept., Colorado State University

$$\begin{aligned}\sigma_i &= C_{ij}^E S_j - e_{ik} E_k \\ D_k &= e_{kj} S_j + \epsilon_{kl} E_l\end{aligned}\quad (1)$$

where σ_i and S_i are the mechanical stress and engineering strain vectors; E_k is the electric field vector; D_k is the electric displacement component; C_{ij} is the stiffness tensor; e_{ik} is the piezoelectric tensor; and ϵ_{kl} is the electric permittivity tensor of the material.

Discrete-Layer Laminate Theories. The developed discrete-layer laminate theories assume piecewise continuous approximations along the z -axis for both displacement and electric potential fields (see Fig. 1) of the following form:

$$\begin{aligned}u(x,y,z,t) &= \sum_{j=1}^N u^j(x,y,t) \Psi^j(z), & v(x,y,z,t) &= \sum_{j=1}^N v^j(x,y,t) \Psi^j(z) \\ w(x,y,z,t) &= \sum_{j=1}^N w^j(x,y,t) \Psi^j(z), & \phi(x,y,z,t) &= \sum_{j=1}^N \phi^j(x,y,t) \Psi^j(z)\end{aligned}\quad (2)$$

As seen in Fig. 1, the above kinematic assumptions entail the capability to control the detail of approximation through the thickness of a piezoelectric laminate, can capture the local response and are suitable for modelling thick piezoelectric structures.

Finite Element Formulation. Combination of eqs. (1-2) with the Hamilton's principle (equations of motion) for a piezoelectric medium provide the basis for the development of structural solutions. Of particular importance is the development of finite element techniques for structural problems with general boundary, geometry and material configurations. Beam, plate and shell elements have been developed as described in refs. [1-3]. In all cases the discretized governing dynamic equations of the smart composite structure are expressed in the following compact form:

$$\begin{bmatrix} [M_{uu}] & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{\phi}^S\} \end{Bmatrix} + \begin{bmatrix} [K_{uu}] & [K_{u\phi}^{SS}] \\ [K_{\phi u}^{SS}] & [K_{\phi\phi}^{SS}] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{\phi^S\} \end{Bmatrix} = \begin{Bmatrix} \{F(t)\} - [K_{u\phi}^{SA}] \{\phi^A\} \\ \{Q^S(t)\} - [K_{\phi\phi}^{SA}] \{\phi^A\} \end{Bmatrix}\quad (3)$$

where the electric potential vector has been subdivided in a sensory component ϕ^S representing the voltage output at the sensors, and an active component ϕ^A representing the voltage imposed on the active piezoelectric layers. The left-hand side includes the unknown electromechanical response of the structure $\{u, \phi^S\}$, that is, the resultant displacements and voltage at the sensors. The right-hand includes the excitation of the structure in terms of mechanical loads, applied voltages and applied electric charge on the actuators. The capability of the approach to model the response of smart structures with embedded piezoelectric actuators and sensors is obvious in eq. (3).

Evaluations

Hybrid Simply-Supported Plate. The free-vibration response of a 5-ply [p/0/90/0/p] laminated simply-supported square plate incorporating continuous piezoceramic PZT-4 layers (indicated with letter p) and Graphite/Epoxy composite plies is presented here. Results are compared with an exact piezoelectricity solution [4] for this plate. The extreme case of a thick plate (free span/thickness ratio of 4) is presented. Figs. 2 and 3

show respectively the through-the-thickness distributions of the modal in-plane displacements and stresses corresponding to the fundamental mode. Clearly, the developed finite elements (FE) yield excellent agreement with the exact solution. Moreover, the results show that other simplified theories (simplified linear displacement and electric fields, single layer assumptions) may result in significant deviations and errors in the case of thick sections (Fig. 3).

Composite Plate with Discrete Piezoelectric Patches. The capability to model smart structures with discrete piezoelectric actuators/sensors is demonstrated in Fig. 3, where the predicted transverse displacements for a $[0/\pm 45]_s$ Gr/Epoxy cantilever plate with 15 piezoceramic actuators bonded on each side are correlated with measured data reported by Crawley and Lazarus [5]. The predicted transverse displacements, which are induced by an applied uniform electric field of 394 V/mm of opposite polarity at the upper and lower piezoelectric patches are in very good agreement with the measured data.

Summary

Laminate and structural mechanics and the corresponding coupled electromechanical models for the dynamic analysis of smart composite beam, plate and shell structures with embedded piezoelectric actuators and sensors developed in NASA-Lewis were overviewed, and their unique capabilities were summarized. The mechanics and the formulations have been encoded into research codes. Two application cases were presented to illustrate the extreme capabilities of the developed mechanics to model thick and/or thin piezoelectric composite structures; continuous or discrete piezoelectric devices; and the local response and related phenomena in a piezoelectric laminates.

References

1. Saravanos D.A. and Heyliger P.R. "Coupled Electromechanical Response of Composite Beams with Embedded Piezoelectric Sensors and Actuators," *Journal of Intelligent Material Systems and Structures*, Vol. 6, No. 3, 1995, pp. 350-363.
2. Heyliger P. R., Ramirez G. and Saravanos D. A., "Coupled Discrete-Layer Finite Elements for Laminated Piezoelectric Plates," *Communications in Numerical Methods in Engineering*, Vol. 10, pp. 971-981, 1994.
3. Heyliger P. R., Ramirez G. and Pei K.C., "Discrete-Layer Piezoelectric Plate and Shell Models for Active Tip-Clearance Control," *NASA CR 195383*, Oct. 1994.
4. Heyliger P. R. and Saravanos D. A., "Exact Free-Vibration Analysis of Laminated Plates with Embedded Piezoelectric Layers," *Journal of Acoustical Society of America*, in press.
5. K. B. Lazarus and E. F. Crawley, "Induced Strain Actuation of Composite Plates", *GTL Report No. 197*, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1989.

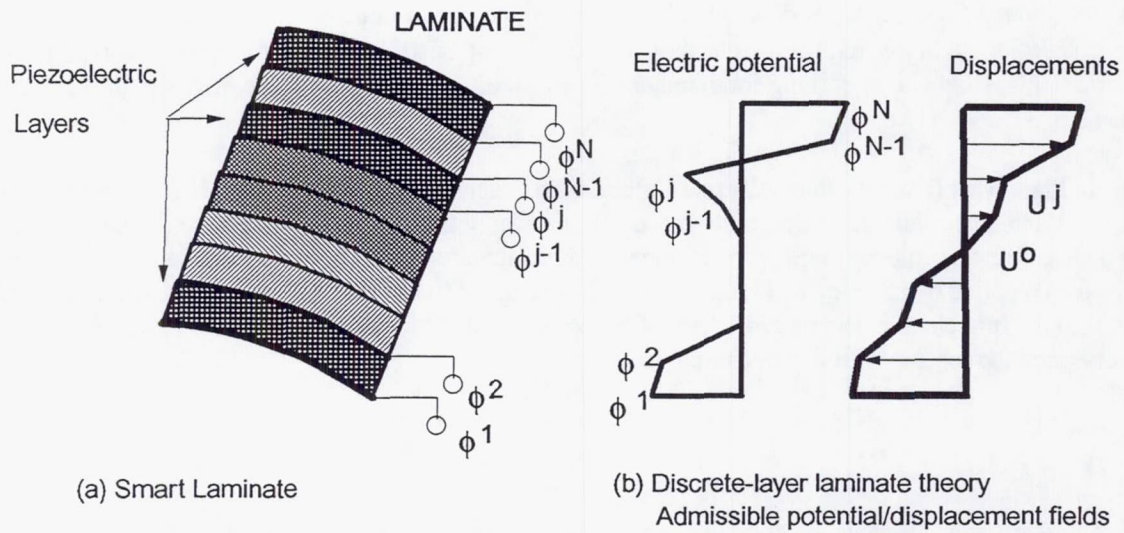


Figure 1 Typical sensory/active laminate configuration . (a) Concept ; (b) Assumed displacement and electric potential fields through the thickness of the laminate

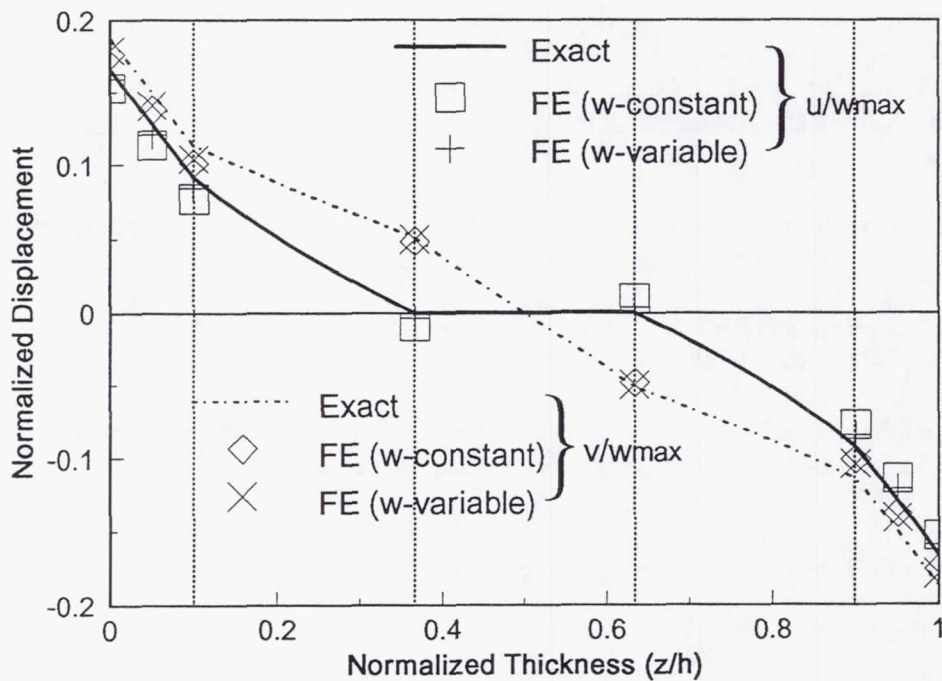


Figure 2 Through-the-thickness in-plane displacement fields of the fundamental mode in a thick $[p/0/90/0/p]$ simply supported square plate. Thickness aspect ratio $\alpha/h=4$.

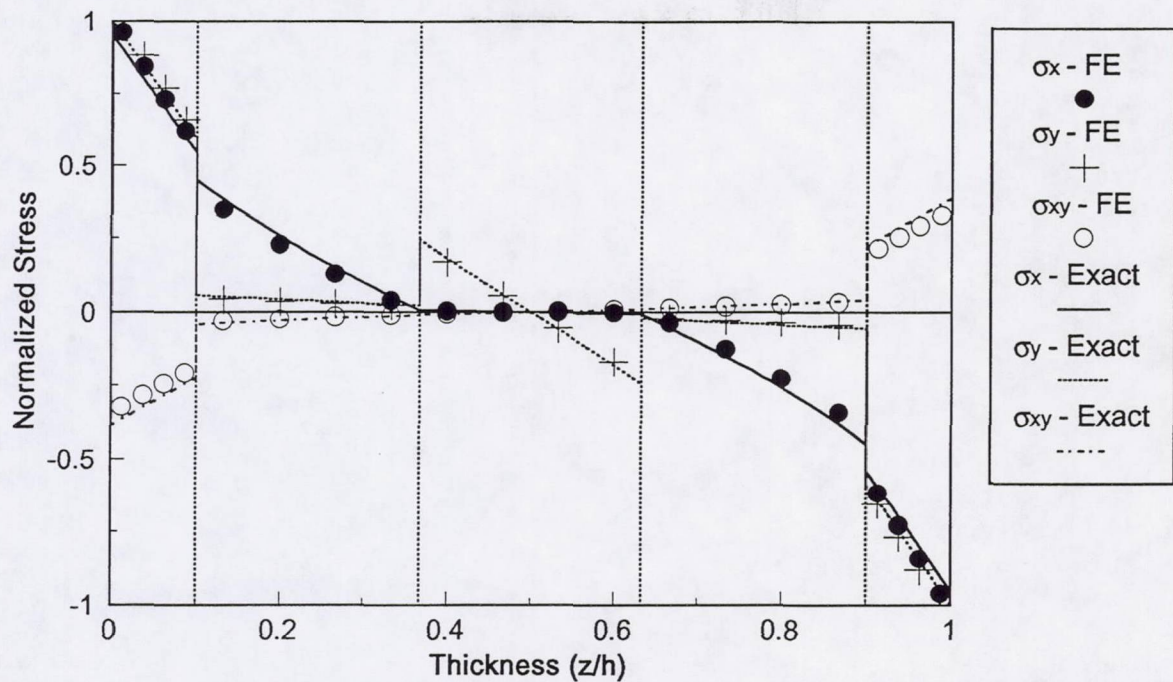


Figure 3 Through-the-thickness intralaminar stresses corresponding to the fundamental mode in a thick $[p/0/90/0/p]$ simply supported square plate. Thickness aspect ratio $\alpha/h=4$.

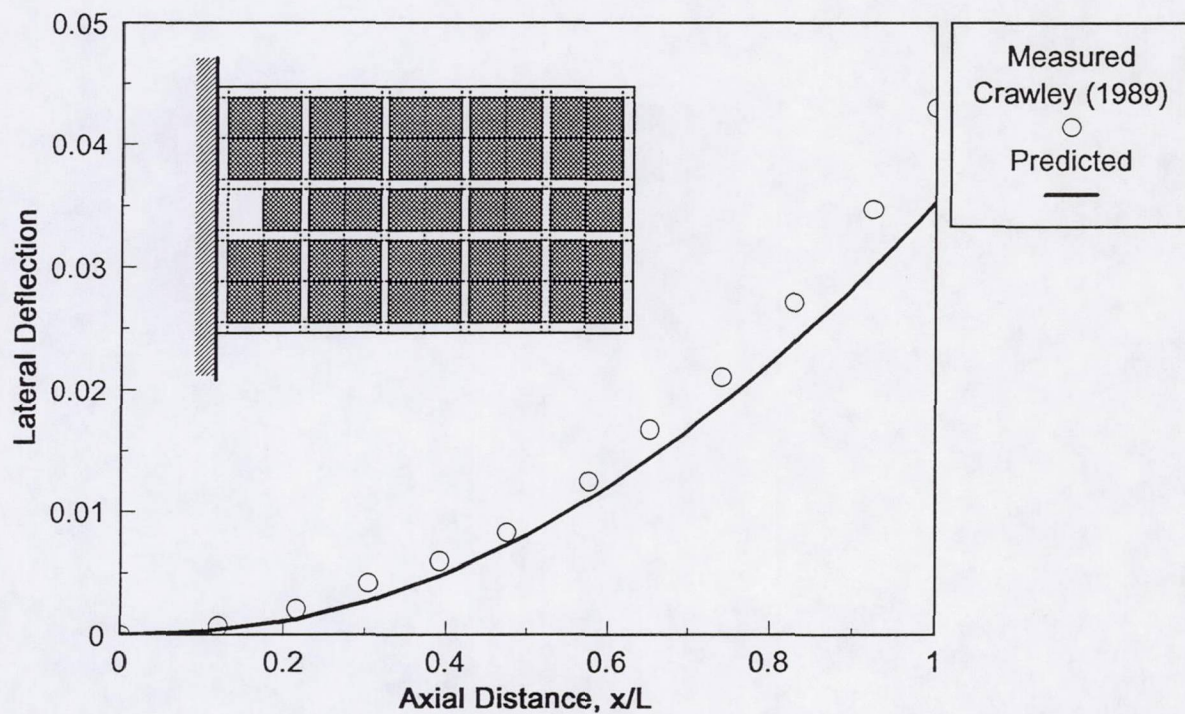


Figure 4 Predicted and measured deformation of a $[0/\pm 45]_s$ Gr/Epoxy cantilever plate beam with distributed discrete piezoceramic actuators.

Page intentionally left blank

FINITE ELEMENT SIMULATION OF SMART STRUCTURES

Y. Lawrence Cui and M. Panahandeh

Berkeley Applied Science and Engineering Inc.

Suite 530, 5 Third Street

San Francisco, CA 94103

528-64

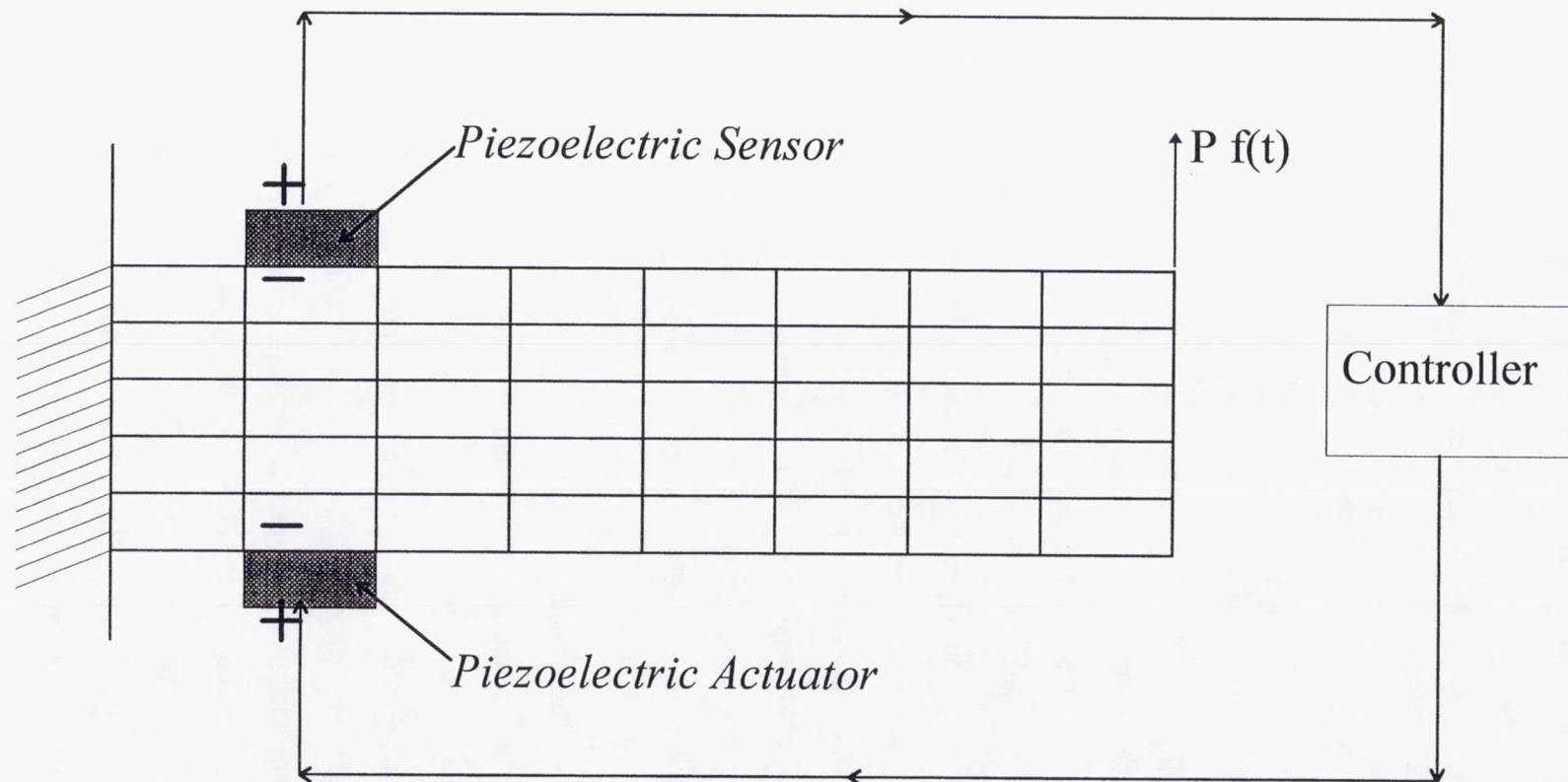
61493

2351151

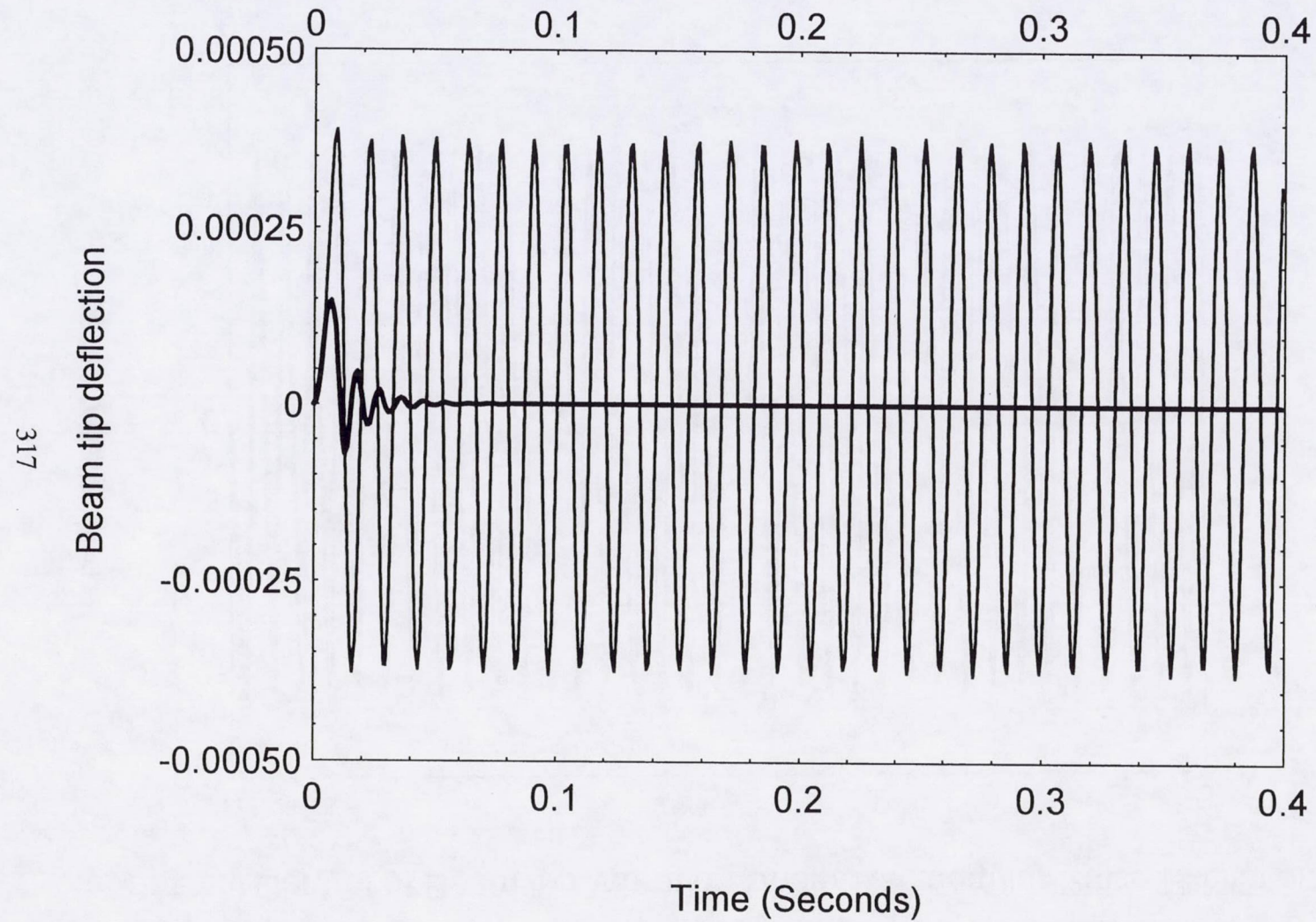
4P.

Finite element equations representing the behavior of piezoelectric materials when bonded to a typical structure and used as sensors and actuators were developed. Emphasis was placed on generating sensor output equations of piezoelectric sensors and responses of a typical structure bonded with piezoelectric sensors and actuators on the basis of finite element formulation. The model can predict not only structural responses due to both mechanical and electrical loading but also electrical potential due to mechanical or thermal effects. The resulted finite element equations were then used for simple control design and performance evaluation. In the control algorithm, voltages coming out from piezoelectric sensors, which are proportional to strains at sensing locations, are taken as input. The voltages applied to the piezoelectric actuators are used as output. The feasibility of integrating control algorithm with the element routine developed herein and FEAP was demonstrated. In particular, optimal independent modal space control was implemented in a software package on the basis of finite element formulation. A rudimentary finite element-control algorithm package was also developed to evaluate the performance of candidate control laws. A few numerical simulations using the software package developed herein were given. The integrated software package will provide a design tool to address issues such as how adaptive smart systems will scale to a full size aircraft, the amount of piezoelectric materials and the powers needed to actuate it for desired performance. It will also provide a viable new structural control design concept for practical applications in large flexible structures such as aerospace vehicles and aircraft.

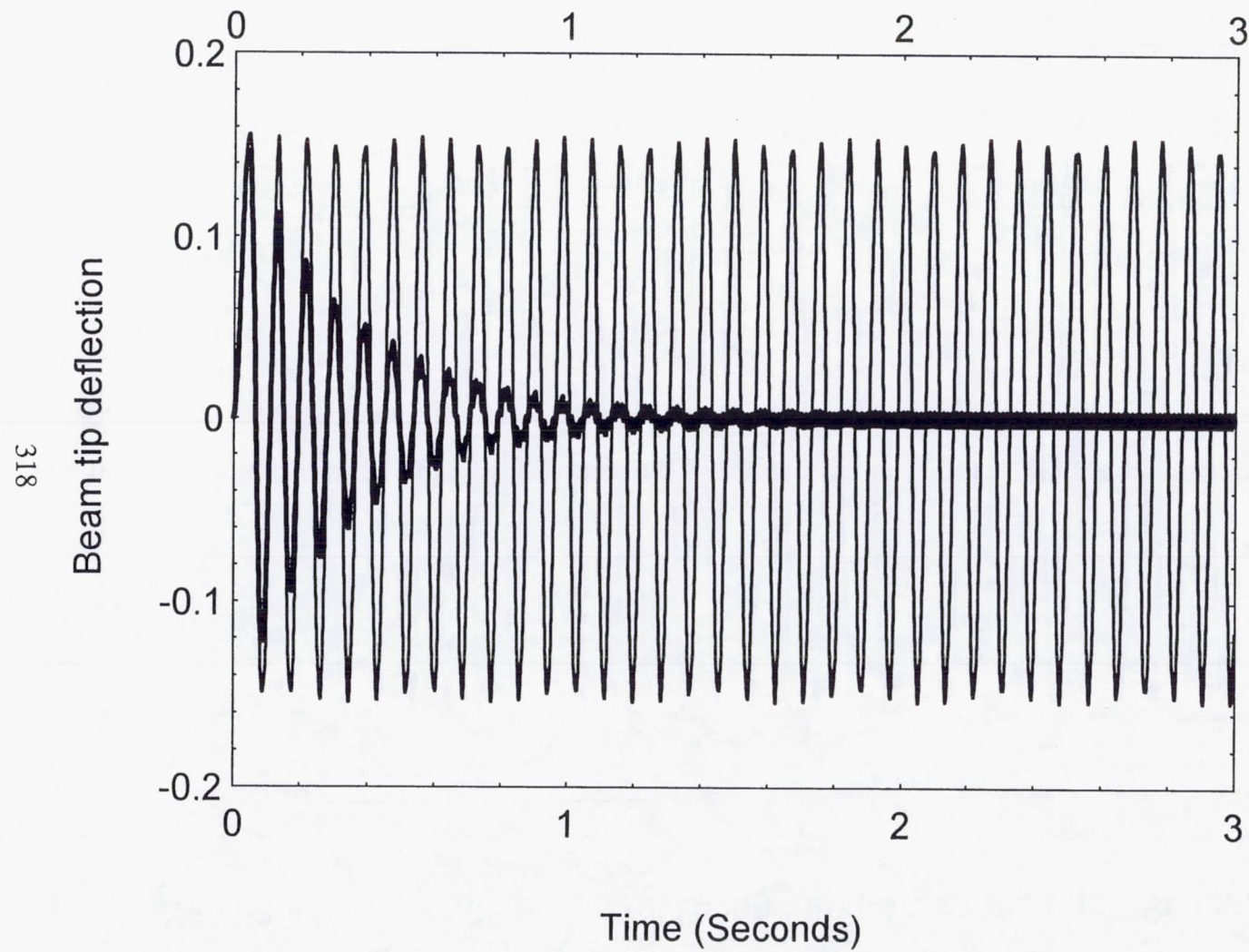
Feedback Control Simulation Via the Integrated FEM-Control Software Package: An Example



Simulation of Vibration Control Using Integrated Package: Sinusoidal Excitation



Optimal Control of Beam Tip Vibration Under Rectangular Pulse Excitation



529-24
61497
035116
6P

Development of a higher order laminate theory for modeling composites with induced strain actuators

Aditi Chattopadhyay and Charles E. Seeley

Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, Arizona, 85287-6106

Fourth Annual Advances in Smart Materials for Aerospace Applications Workshop
NASA Langley Research Center
Hampton, VA, 23681

Abstract

A refined higher order plate theory is developed to investigate the actuation mechanism of piezoelectric materials surface bonded or embedded in composite laminates. The current analysis uses a displacement field which accurately accounts for transverse shear stresses. Some higher order terms are identified by using the conditions that shear stresses vanish at all free surfaces. Therefore, all boundary conditions for displacements and stresses are satisfied in the present theory. The analysis is implemented using the finite element method which provides a convenient means to construct a numerical solution due to the discrete nature of the actuators. The higher order theory is computationally less expensive than a full three dimensional analysis. The theory is also shown to agree well with published experimental results. Numerical examples are presented for composite plates with thicknesses ranging from thin to very thick.

Analysis

A refined higher order displacement field is used which satisfies the requirement of zero transverse shear stresses on the upper and lower surfaces of the plate and is presented as follows.

$$\begin{aligned}
U_1 &= u_{10} + z \left[u_{11} - \frac{4}{3} \left(\frac{z}{h} \right)^2 \left(u_{11} + \frac{\partial u_{30}}{\partial x} \right) \right] \\
U_2 &= u_{20} + z \left[u_{21} - \frac{4}{3} \left(\frac{z}{h} \right)^2 \left(u_{21} + \frac{\partial u_{30}}{\partial y} \right) \right] \\
U_3 &= u_{30}
\end{aligned} \tag{1}$$

where U_1 , U_2 , and U_3 are the displacements, u_{10} and u_{20} are the inplane displacements defined at the midplane, u_{30} is the transverse displacement, u_{11} and u_{21} are rotations and h is the thickness of the plate. Induced strain via piezoelectric actuation enters through the constitutive relationship for the k th ply as follows.

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}_k = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 & 0 & 0 & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 & 0 & 0 & \bar{Q}_{26} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{Q}_{44} & \bar{Q}_{45} & 0 \\ 0 & 0 & 0 & \bar{Q}_{45} & \bar{Q}_{55} & 0 \\ \bar{Q}_{16} & \bar{Q}_{26} & 0 & 0 & 0 & \bar{Q}_{66} \end{bmatrix}_k \begin{bmatrix} \epsilon_1 - \Lambda \\ \epsilon_2 - \Lambda \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}_k \tag{2}$$

where Λ is the piezoelectric strain and the quantities $\bar{Q}_{ij}$ are calculated in terms of the orthotropic stiffness Q_{ij} through the usual transformation techniques.

The principle of stationary potential energy is used to construct the finite element model. Therefore, general boundary conditions can be imposed. The model is both accurate and computationally efficient. It is also shown to agree well with experimental results.

Results

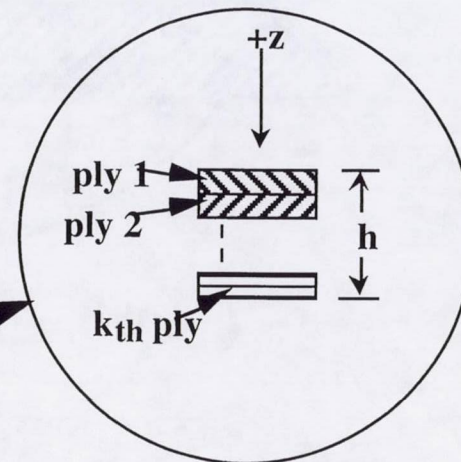
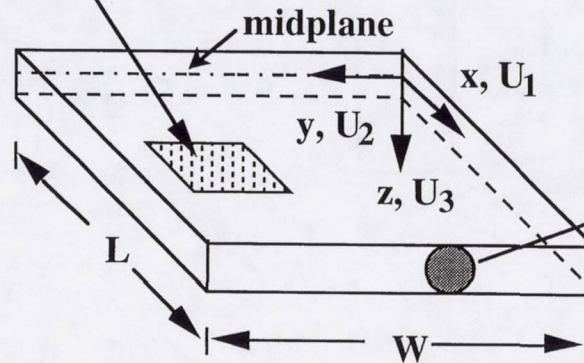
A cantilever composite plate with a parabolic distributed load is investigated which represents the principal load carrying member of an airplane wing which is assumed to have a parabolic aerodynamic lift distribution. Significant deviations are observed for the refined higher order theory compared to classical theory for thicker plates where transverse shear stresses become important. The refined theory can more accurately predict stresses and displacements where classical theory fails. Localized effects due to piezoelectric actuation are more accurately represented using the refined theory as well.



COMPOSITE PLATE WITH PIEZOELECTRIC ACTUATOR



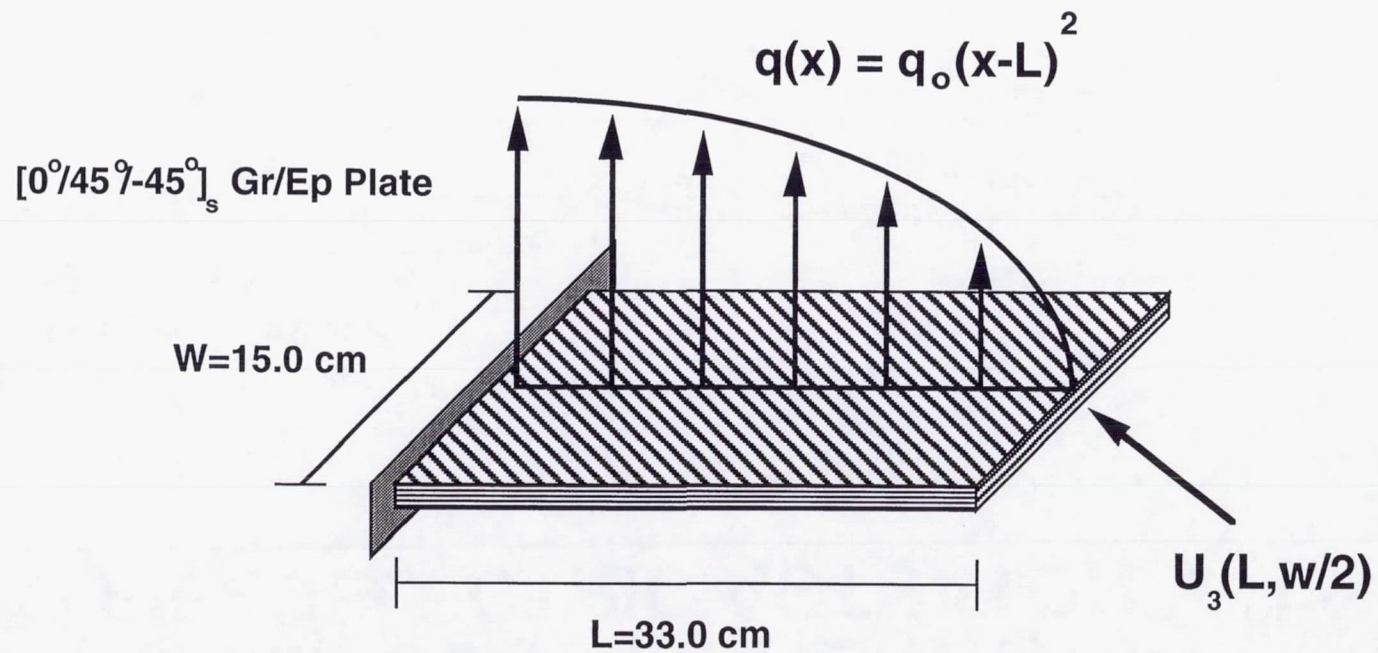
Piezoelectric actuator



wall cross section

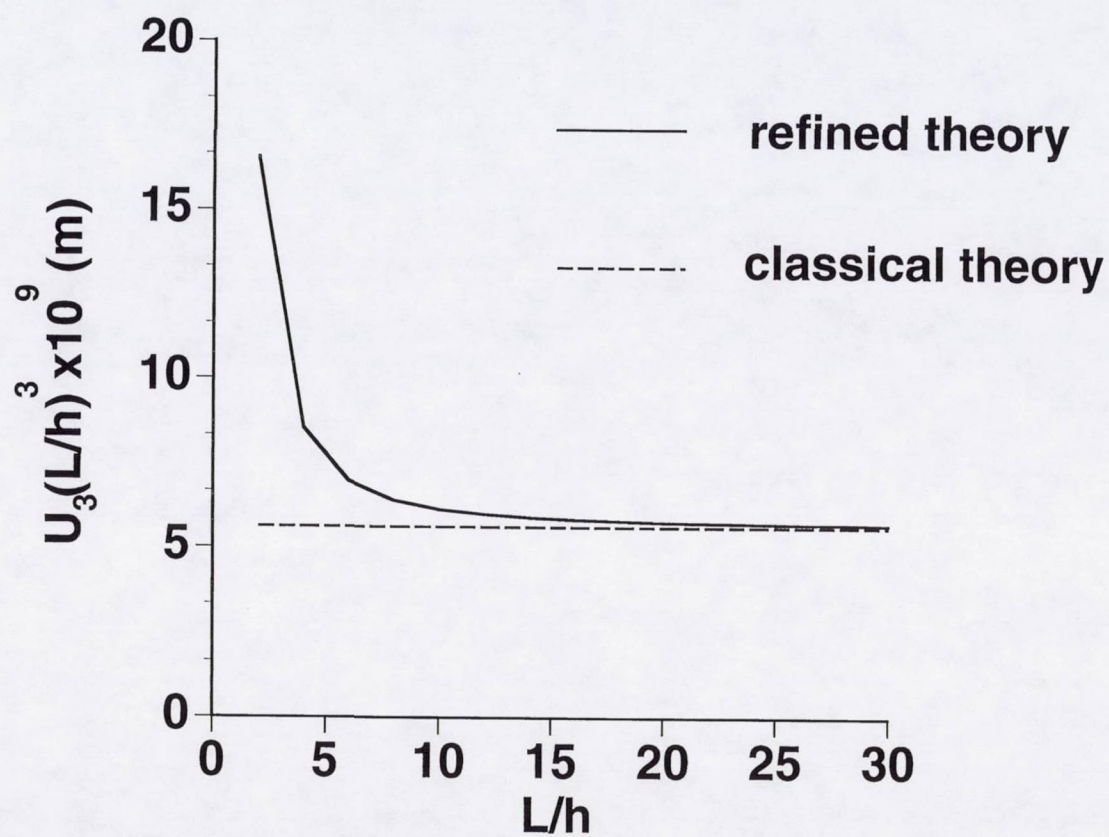


COMPOSITE PLATE WITH PARABOLIC DISTRIBUTED LOAD





TRANSVERSE TIP DISPLACEMENT



Page intentionally left blank

530-27
61499
235117
4p.

ON THE SENSITIVITY OF PIEZOCERAMICS AND PIEZOPOLYMERS IN STRUCTURAL INTEGRITY MONITORING OF LARGE TRUSSES

By

A. O. Abatan, M. W. Lin and E. Mintz
High Performance Polymers and Ceramics Center
Clark Atlanta University
Atlanta, GA 30314

SYNOPSIS

An analytical assessment has been made of the reliability of using integrated micro-actuators and sensors in the form of piezoceramics and piezopolymers as joint integrity monitors in trussed systems. The concept is first implemented for a simple structure which consists of two truss members with a 45° lift angle joined at the apex. A piezoceramic patch (or piezopolymer film) bonded on the surface of one of the members at a location near the joint is used as a collocated actuator/sensor (Figure 1). The overall structural dynamic response under an excitation was modeled by finite element method. Different degrees of nodal constraints at the joints representing various degrees of joint integrity are employed. The resulting dynamic response showed distinct responses for varying joint stiffnesses. Parallel experimental work on a truss model using a multichannel data acquisition system and a digital signal analyzer confirms the results from analysis (Figure 2 and Figure 3).

We further studied the sensitivity of the micro-sensors to the behavior of joints of large arch truss structure (Figure 4). Results obtained for large trusses with many degrees of freedom indicate optimum locations of sensors for which the dynamic response signatures are distinct and distinguishable for relatively small changes in joint integrity and/or structural geometry. Computations based on finite element modeling show that locating the single actuator/sensor at the joint corresponding to the first loss of static stability appear optimal. Hence, static stability analysis of complex trusses can give us a good indication of the optimum placement of sensors for maximum response. This observation is important if few distributed sensors and actuators are available for placement in constructed facilities made from large trusses with many degrees of freedom.

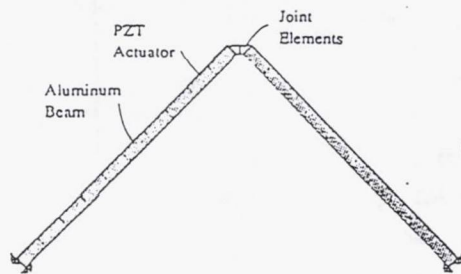
As an extension of this work, a dynamic response signature identification technique to monitor in-service degradation of joints is under development for application to the monitoring of the integrity of adhesive joints in composite structures.

Acknowledgment

The authors would like to acknowledge the support of NASA for this research under the NASA Grant Number NAGW-2939 for the High Performance Polymers and Ceramics (HiPPAC) Center at Clark Atlanta University.

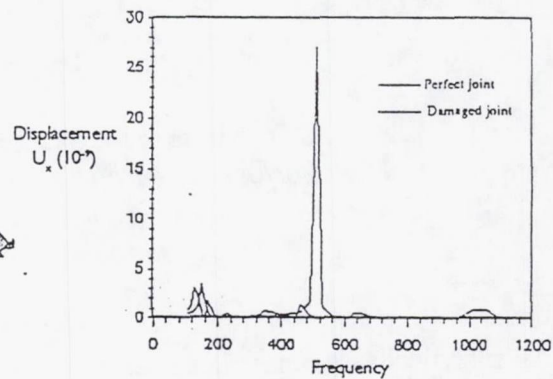
DYNAMIC RESPONSE OF A JOINTED STRUCTURE EXCITED BY PZT ACTUATORS

FEM MODEL



- In case (1), the material property of the aluminum beam was assigned to the joint elements to simulate a 'perfect' joint
- In case (2), a relatively compliant material property (with 50% stiffness of the aluminum) was assigned to the joint elements to simulate a partially damaged joint
- The PZT actuator was used to excite the structure

FREQUENCY RESPONSE OF THE STRUCTURE



- The frequency responses of the two cases are distinguishable, particularly at high frequency

Figure 1

Experiment

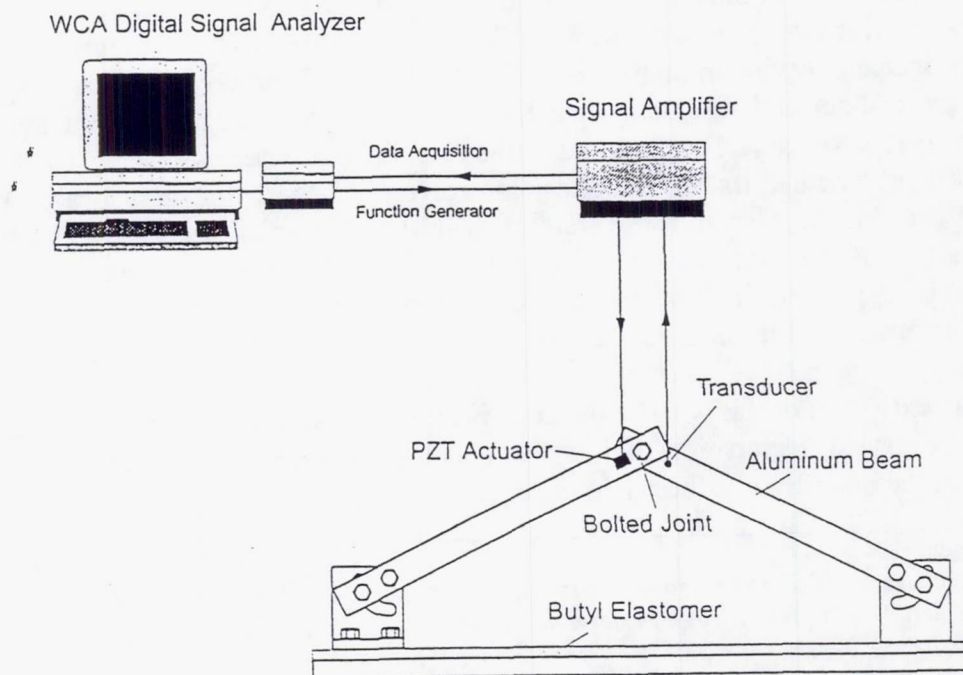


Figure 2

Experimental Results

Frequency Response

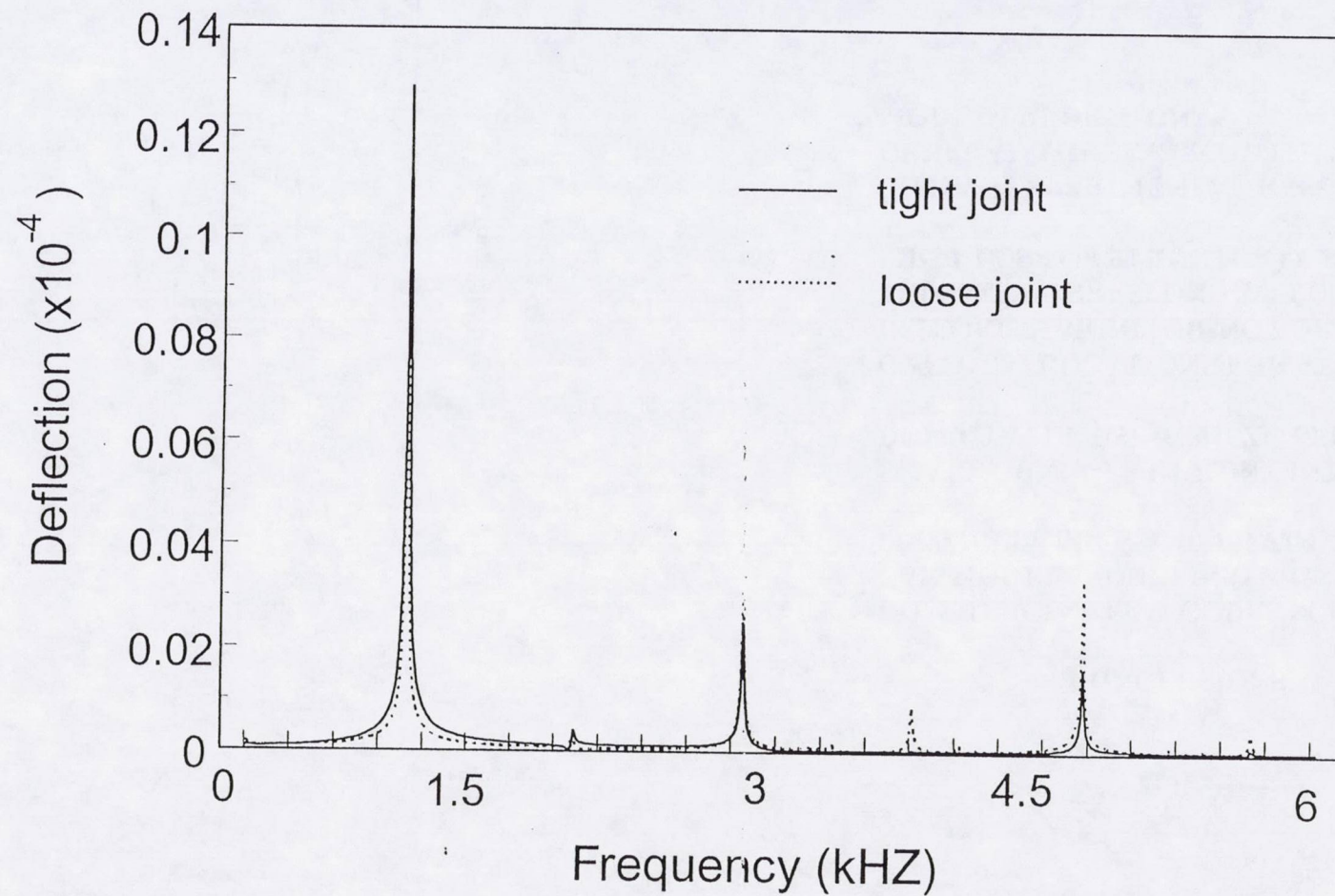
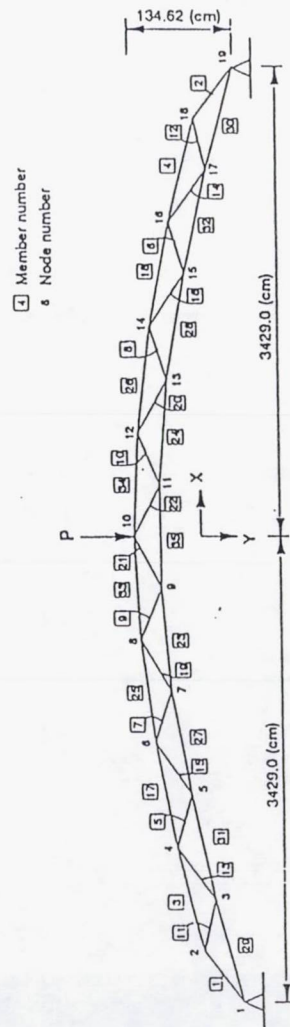


Figure 3



Arch-Truss Structure

Figure 4

CONCLUSIONS

1. COMMERCIAL FEM CODES SUCH AS ANSYS CAN MODEL INDUCED-STRAIN ACTIONS OF PIEZOCERAMICS AND PIEZOPOLYMERS
2. SMALL CHANGES IN JOINT INTEGRITY ARE DETECTABLE USING PIEZO SENSORS
3. OPTIMUM LOCATIONS FOR STRUCTURAL INTEGRITY MONITORING FOR LARGE TRUSSES CORRESPOND TO LOCATIONS OF FIRST LOSS OF STRUCTURAL STABILITY
4. INITIAL EXPERIMENTAL RESULTS ARE IN GENERAL AGREEMENT WITH THE FEM MODEL PREDICTIONS

531-35
61501

CONSTRUCTION OF A PIEZORESISTIVE "NEURAL SENSOR" ARRAY

6P.
035118

W. B. Carlson, W. A. Schulze, P. M. Pilgrim
New York State College of Ceramics
Alfred, New York 14802

Introduction

The construction of a piezoresistive - piezoelectric sensor (or actuator) array is proposed using 'neural' connectivity for signal recognition and possible actuation functions. A closer integration of the sensor and decision functions is necessary in order to achieve intrinsic identification within the sensor. A neural sensor is the next logical step in development of truly 'intelligent' arrays. This proposal will integrate 1-3 polymer piezoresistors and MLC electroceramic devices for applications involving acoustic identification. Prior work has focused on the development of piezoresistive composites in order to study the possibility of using resistor-capacitor control elements in "smart" actuation. This work extends the integration of these devices into an array structure in order to analyze and 'train' sensors for specific responses. The "intelligent" piezoresistor -piezoelectric system incorporates printed resistors, composite resistors, and a feedback for the resetting of resistances[1]. A model of a design is proposed in order to simulate electromechanical-resistor interactions. The goal of optimizing a sensor geometry for improving device reliability, training, & signal identification capabilities is the goal of this work. At present, studies predict performance of a 'smart' device with a significant control of 'effective' compliance over a narrow pressure range due to a piezoresistor percolation threshold[2]. An interesting possibility may be to use an array of control elements to shift the threshold function in order to change the level of resistance in a neural sensor array for identification, or, actuation applications.

The proposed design employs elements of: 1) conductor loaded polymers for a "fast" RC time constant response; and, 2) multilayer ceramics for actuation or sensing and shifting of resistance in the polymer [1,2]. Other

material possibilities also exist using magnetoresistive layered systems for shifting the resistance. It is proposed to use a neural net configuration to test and to help study the possible changes required in the materials design of these devices. Numerical design models utilize electromechanical elements, in conjunction with structural elements in order to simulate piezoresistively controlled actuators and changes in resistance of sensors. The construction of these devices may show significant improvement in ability to interrogate signals and in the control of effective compliance. This work focuses on the development a variety of series/parallel interconnected piezoresistive control elements for the neural sensing function.

Array Fabrication

A set of piezoresistive sensors[17,18] that can be electromechanically controlled will be fabricated for the array. These devices will be tested to determine their effective resistance change as a function of applied stress and conductor loading for different polymer stiffnesses. If possible, polymer materials will be identified from those previously tested in composite PTCR devices [19].

System Array

A "smart" material in this case is considered to be a composite material with integral resistor-capacitor electronics which provides a variable, predictable response to a stimulus. For the context of this work, the smart material package will be used for sensing a stress or pressure disturbance and responding in an appropriate manner, either through actuation or voltage change. Many smart material package configurations exist, but the usage of these systems may be limited because of the remoteness of the amplifying electronics on its operation. Sensors cannot provide enough response (voltage) to drive an actuator effectively without amplification. This requires feedback electronics which are inherently limiting with respect to power consumption, space, complexity of wiring, and the response time (RC time constant). Alternatively, the proposed system requires only a DC voltage source. All controlling electronics will

be attached, embedded, or printed using thick film technology, directly on the device. The device would be a "plug-in" module.

Actuator Component

Work is focusing on an array of PZT electroceramics which will be obtained from multilayer tape-casting procedures. Binder burnout and co-firing/sintering of the laminated material will be performed using ceramic processing principles [3,4,5,6].

Piezoelectrics and biased electrostrictors are both materials with an electric dipole that can be reoriented under applied field. Since the dipole orientation and magnitude are coupled to the crystallographic lattice, this results in an induced strain with changing field [7]. Regardless of the specific type of electromechanical material, when an electric field is applied in the direction of the existing dipole orientation, the dipole will be strongly altered parallel to its existing orientation. Associated with this motion is an enlargement or contraction of the unit cell [8]. This effect can be seen macroscopically as dilation or contraction of the piece. This is the converse piezoelectric effect. However, the total strain available from the material is less than 0.1% at common, ~ 0.55 MV/m, electric fields. This led previous researchers to develop the multilayer cofired actuator and to increase the electric field [3,9].

In the piezoelectric case, these electromechanical materials are used for a wide variety of medical, industrial and military uses [10,11,12,13]. Uses of the electrostrictors are not yet as extensive; however, they have been demonstrated for sonar transducers and have seen extensive academic research as smart materials [9,14]. Since a piezoelectric case can be used to approximate an electrostrictor under DC bias, this initial example will consider them identically. As a further simplification, the material will be driven only by a DC field.

Piezoresistive Control Component

The loaded polymer piezoresistive material is one that displays a change of resistance that varies with application of stress. This effect is particularly appealing as a control effect because the very large (more than 2 orders of magnitude) change in response provides a large dynamic range. In initial studies, carbon-loaded epoxy materials were investigated. In this proposal carbon or metal systems are to be manufactured. Three phase systems may also offer broader sensitivity over the range of pressures. The mechanism of piezoresistivity is related to connectivity and percolation of the conductive phase (carbon or metal) in the insulating epoxy matrix [15]. Here, the piezoresistive material was used as the sole control over the power source.

Although these piezoresistive materials have been used commercially, the effects of multiphasic composite piezoresistors are difficult to model [16]. In this work this complexity was dealt with by fitting a function relating stress and resistance to the behavior of various composites that have structurally related properties involving anisotropic materials used as loading (i.e., such as platelet carbon in epoxy) [17].

Electronic Control Circuit

The major changes of the resistance of the piezoresistor under applied load are incorporated into the control circuit by a resistance bridge. This circuit was used to control the DC voltage to the actuator. In practice, the fixed resistors would be screen printed onto an inactive surface of the system using thick film technology. A particular variation of this design is to backfill the multilayer actuator with sensor "control layers". A very lacy electrode mixed with low hardness epoxy may be oppositely connected to effect a piezoresistor. Two electrically independent piezoresistors are needed to improve the control authority and input discrimination. For the design work, however, they were modeled together.

Anticipated Impact on Sensor Development

In combination with initial measurements of the piezoresistor properties under an applied forces, this type of 'intelligent' sensor should help to further the applicability of the 'smart' devices and the integration of sensors into 'decision making'. This work will identify designs and materials for use in these electromechanical sensor/actuator packages for possible use in advanced microfabrication facilities. This next logical step could allow the full impact of local sensor decision making to be realized. Practical optimization of the electronics and mechanical interaction will remain to be the limit on the eventual use of these devices.

References

1. W.A. Schulze and W.B. Carlson, ARO Contract No. DAAL03-92-G-0374.
2. J. M. Frommelt, S. M. Pilgrim, W. B. Carlson, and W. A. Schulze, "Modeling Of Piezoresistively-Controlled Electromechanical Smart Material," presented at the International Conference on Intelligent Materials, Williamsburg, VA (June 1994).
3. L.S. Bowen, T. Shrout, and W.A. Schulze, "Piezoelectric Properties of Internally Electroded PZT Multilayers," *Ferroelectrics*, **27**, pp. 59-62, (1980).
4. AVX Corp., "Electroactive Actuators", Technical Brochure S-7912.5 MEPA-C, Myrtle Beach, SC, (1991).
5. EDO Western Corp., "Piezoelectric Ceramics," Technical Brochure EWC 02742 8806 10M, Salt Lake City, UT, (no date).
6. S.R. Winzer, N. Shankar, A.P. Ritter, "Designing Cofired Multilayer Electrostrictive Actuators for Reliability", *J. Am. Ceram. Soc.*, **72**, No. 12, pp. 2246-2257, (1989).
7. J.F. Nye, *Physical Properties of Crystals*, Oxford University Press, Oxford, UK (1971).
8. B. Jaffe, W.R. Cook, and H. Jaffe, *Piezoelectric Ceramics*, Academic Press, NY, (1971).

9. S. M. Pilgrim, A.E. Bailey, M. Massuda, F.C. Poppe, and A.P. Ritter, "Fabrication and Characterization of PZT Multilayer Actuators," *Ferroelectrics*, (in press 1994).
10. P.N.T Wells, *Biomedical Ultrasonics*, Academic Press, London, (1977).
11. K.S. Suslick, Ed., *Ultrasound: Its Chemical, Physical, and Biological Effects*, VCH (1988).
12. L.E. Cross, R.E. Newnham, A.S. Bhalla, J.P. Dougherty, and J.H. Adair, "Piezoelectric and Electrostrictive Materials for Transducer Applications", Annual Report for ONR Contract N00014-89-J-1689, (1991).
13. S.M. Pilgrim, M. Massuda, J.D. Prodey, and A.P. Ritter, "Electrostrictive Sonar Drivers for Flexensional Transducers", *Transducers for Sonics and Ultrasonics*, Eds. M. McCollum, B.F. Hamonic, and O.B. Wilson, Technomic, Lancaster, PA (1993).
14. R.E. Newnham, "Tunable Transducers: Nonlinear Phenomena in Electroceramics", NIST Publication 804., Gaithersburg, MD (1991).
15. E.K. Sichel, *Carbon Black-Polymer Composites: The Physics of Electrically Conducting Composites*, Marcel Dekker, New York, NY (1982).
16. R. Zallen, "The Percolation Model," *The Physics of Amorphous Solids*, 4, pp. 135-204, Wiley, New York, NY (1981).
17. B. Lembke, "A Study in the Forming and Modeling of a Piezoresistive Sensor to be Used in a 'Smart' Device," B.S. Thesis in Ceramic Engineering, New York State College of Ceramics, Alfred, NY (1994).
18. L.L. Rohlfiing, S.M. Pilgrim, R.E. Newnham, and J. Runt, "Size Effects on Percolation Behavior in Multiphasic Composite Thermistors," *J. of Wave-Material Interaction*, 3, No. 4 pp. 301-310 (1988).
19. M. Narkis and A. Vaxman, "Resistivity Behavior of Filled Electrically Conductive Crosslinked Polyethylene," *J. Appl. Polym. Sci.*, 29, 1639-52, 1984.

SHAPE CONTROL OF SOLAR COLLECTORS USING
SHAPE MEMORY ALLOY ACTUATORS

D. W. Lobitz, J. W. Grossman, J. J. Allen and T. M. Rice
Sandia National Laboratories
Albuquerque, New Mexico 87185-0439

C. Liang and F. M. Davidson
Department of Mechanical Engineering
San Diego State University, San Diego, CA 92182-0191

Extended Abstract

Solar collectors that are focused on a central receiver are designed with a mechanism for defocusing the collector or disabling it by turning it out of the path of the sun's rays. This is required to avoid damaging the receiver during periods of inoperability. In either of these two cases a fail-safe operation is very desirable where during power outages the collector passively goes to its defocused or deactivated state. This paper will be principally concerned with focusing and defocusing the collector in a fail-safe manner using shape memory alloy actuators. Shape memory alloys are well suited to this application in that once calibrated the actuators can be operated in an on/off mode using a minimal amount of electric power. Also, in contrast to other smart materials that were investigated for this application, shape memory alloys are capable of providing enough stroke at the appropriate force levels to focus the collector. Design and analysis details presented, along with comparisons to test data taken from an actual prototype, demonstrate that the collector can be repeatedly focused and defocused within accuracies required by typical solar energy systems.

A schematic of the collector/actuator system design is shown in the first slide. Although a continuous edge moment is desirable for deforming the collector, the system of discreet couples shown in the slide offers greater flexibility without a significant loss in collector performance. The view is from the backside of the collector looking through the support system. The support system consists of sixteen radial spokes connected at a central hub. On the end of each spoke a pad is attached from which a couple can be applied to the plate. The couple is applied through an actuator and a post, each mounted on the pad and attached to the plate in such a manner that the plate rotations are not inhibited. On each pad the "x's" denote actuator locations and the "o's" the posts. When activated the actuators pull the plate down against the posts. Thus the desired uniform edge moment is approximated by sixteen equal discrete couples placed uniformly around the circumference of the plate.

The design of shape memory alloy actuators is based on a design approach developed by Liang and Rogers (1992). The initial design of the solar collector requires 16 actuators and each to provide a stroke of 0.060 inches against an equivalent spring rate of 100.9 lb/in (collector plate stiffness). The actuator length is restricted to 2.813 inch because of a structural limit. The initial strain for the actuators is 3%. The actuator consists of two 20 mil wires arranged in parallel. Since the solar panel may operate in a desert environment at a high ambient temperature, for example, 50°C, the SMA actuator must be able to provide complete operation cycles (hysteresis) at these temperatures. For this reason an SMA material with an austenitic start temperature of 109°C was selected for this application.

A photograph of part of the fabricated collector/actuator system is shown in the second slide. The posts can be identified by the large knurled knobs protruding below the bakelite mounting plate. Inboard of the posts are two threaded studs that serve as stops for the SMA actuator which is located between the two stops. The guitar string tuner and its mounting plate are located inboard of the stops. The SMA wire actuator is attached to the tuner, threaded through a small hole in the bakelite plate, up through a hole in the collector, over a rod laying on the collector surface, back through the same hole in the collector, down through another small hole in the bakelite plate and finally attached to a terminal between the post and the stops (thus, the two-wire actuator). The actuators are

532-26
61504
235119
6 P.

heated by passing an electrical current through them. To reach desired temperatures a voltage of 2.25 volts (DC) is required for each actuator, producing a current of approximately 1.5 amps. As the 16 actuators are wired in series, a total voltage of 36.0 volts is applied to the circuit (less than 5 watts/actuator).

Deformations of the collector surface were measured in the laboratory using dial indicators attached to a bridge structure that spanned the horizontally-oriented collector. With the dial indicators in place the actuators were activated and the deformations recorded. The measurements were generally repeatable to within ± 0.004 inches. These measurements are presented in the third slide as the small circles. The solid curve represents nonlinear computational predictions. For each radial position, a number of measurements were taken around the corresponding circumference. To simplify the data presentation, the collector was divided in half and the data for each half assigned to either a positive or negative radial value depending on its half of residence. Thus in the slide, clusters of points are present at each radial value. The spread of the data indicates some deviation from axial symmetry in the deformation pattern. The predicted results have been adjusted to produce an eyeball fit of the data. Although the agreement between the measurements and predictions is reasonably good, the data indicates more of a frying pan like shape (steeper on the sides and flatter on the bottom) than the predictions. The departure of the predicted shape from the desired spherical one, as measured by angular differences in the surface normals at a sample of surface locations, is 2.54 milliradians (rms), which is slightly greater than the usual specifications for solar collectors of this type.

Also in the third slide, the image that is reflected off the collector in its activated state is displayed. The target is attached to the underside of half of a stowed ping-pong table. Although not visible the target contains a grid which indicates that the image is approximately 12 inches in diameter. Due to the crude experimental setup it was difficult to achieve the minimum diameter image by adjusting the distance between the collector and the target. Also, as this data is preliminary, extensive efforts were not taken to adjust the actuator stops to get a precise elliptical image. Nevertheless, the results are quite acceptable when compared to image diameter predictions based on the predicted collector shape (the "cross hairs" superimposed on the actual image), which show that the best image diameters for this collector shape are 8 to 9 inches. As the reflective portion of the collector surface is 32 inches in diameter, the image intensity is approximately 7 suns.

In this paper the design, analysis and testing of a solar collector which is deformed into its desired shape by shape memory alloy actuators is presented. Through analysis and testing the actuators met and exceeded design specifications. The collector/actuator system prototype, when activated, demonstrated acceptable performance that was in reasonable agreement with analytical predictions. The deviations of the actual shape of the collector from the desired spherical one were approximately 25% greater than typical requirements of the solar energy community. Preliminary solar testing produced an image slightly larger than that predicted with an intensity of approximately 7 suns.

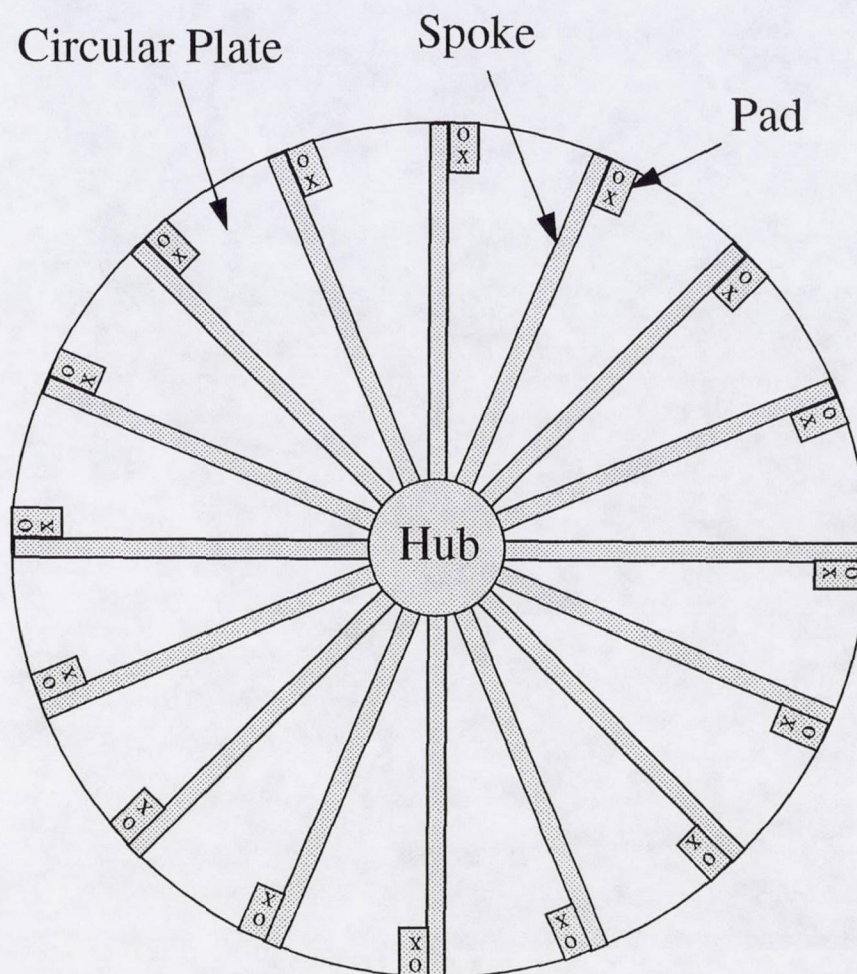
Computations have been completed that indicate collector shapes much closer to spherical and with smaller focal lengths can be achieved by moving the actuators inward to a radius of approximately 6 inches. This would require actuators with considerably more stroke and some alternate SMA actuators are currently under consideration. Whatever SMA actuator is finally chosen for this application, repeatability and fatigue tests will be required to investigate the long term performance of the actuator.

The feasibility of using SMA actuators to shape solar collectors has been demonstrated. As the design evolves there are a number of potential benefits over current practices in the areas of simplicity, economics and maintenance.

Design Description



Structural Dynamics and Vibration Control Department

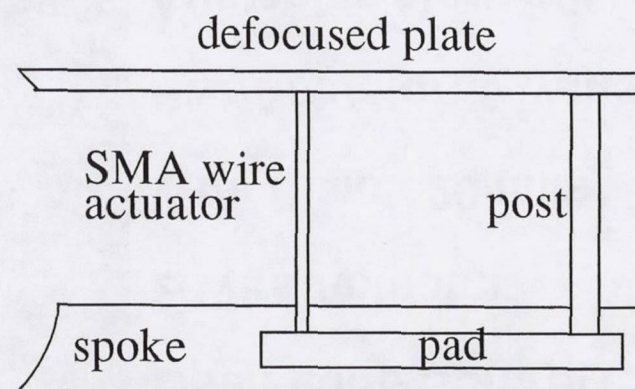


Desired Focal Shape: Spherical

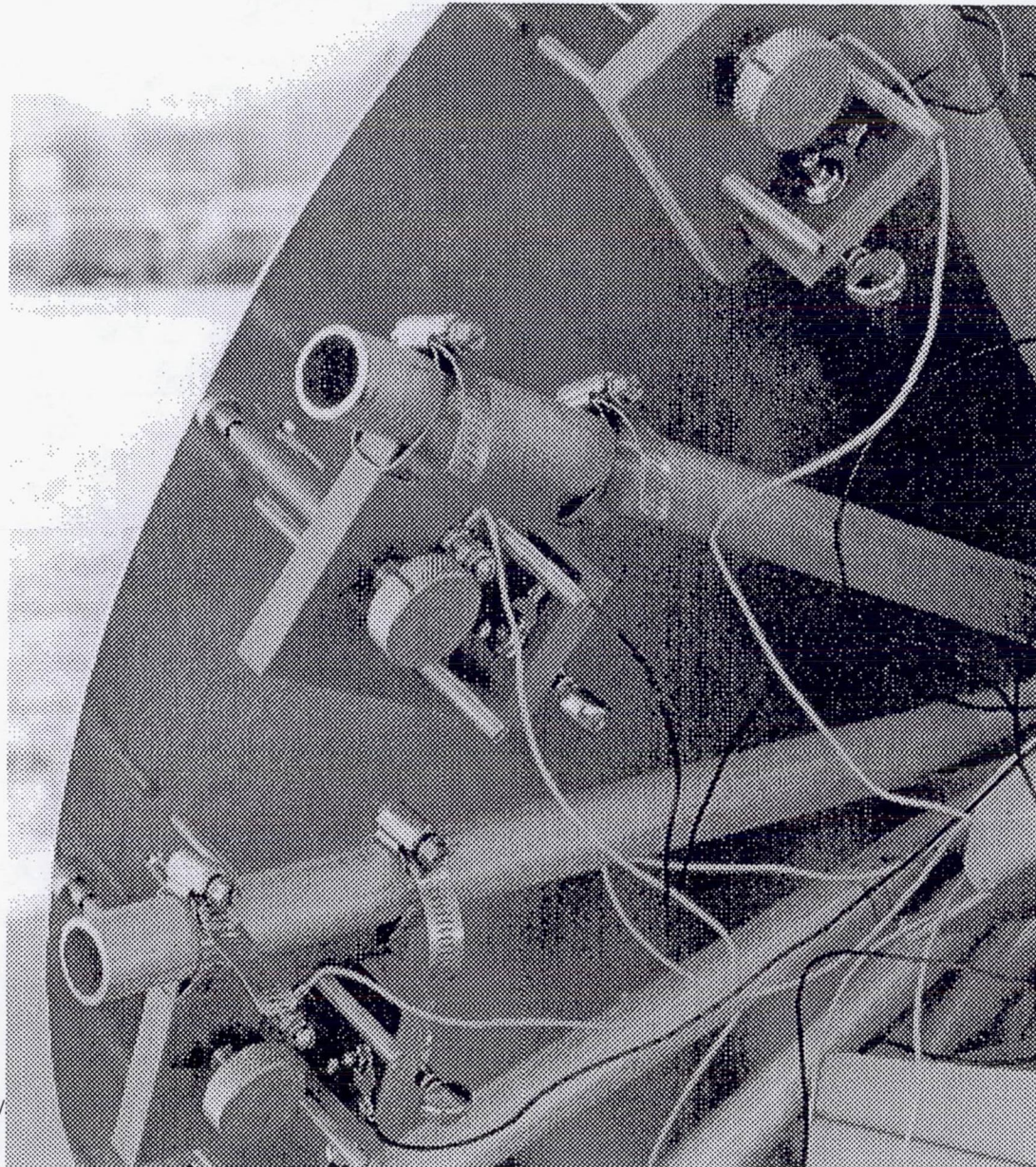
Plate Diameter: 3 feet

Focal Length: 30 feet

Center Disp.: 0.2 inches



Slide 1



Open Loop Control

2-Wire Actuator

Wire Diam.: 20 mils

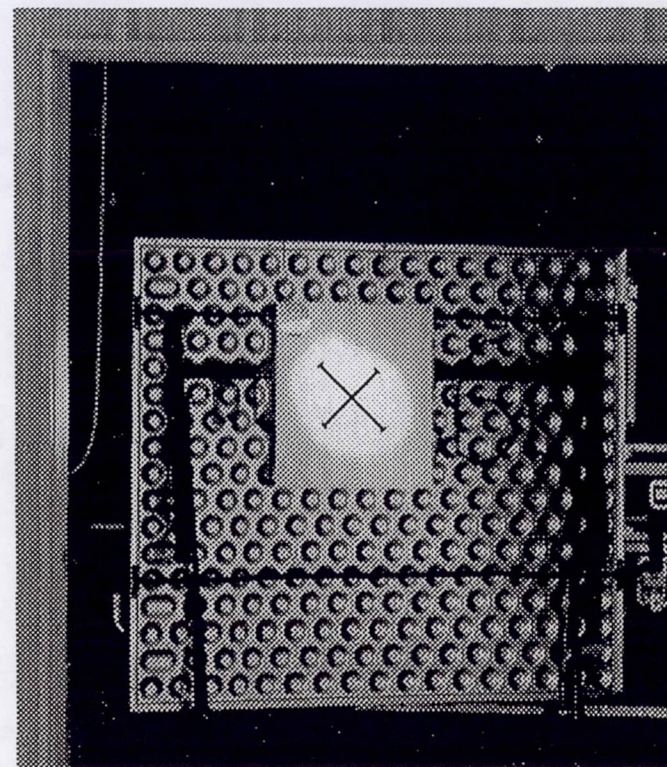
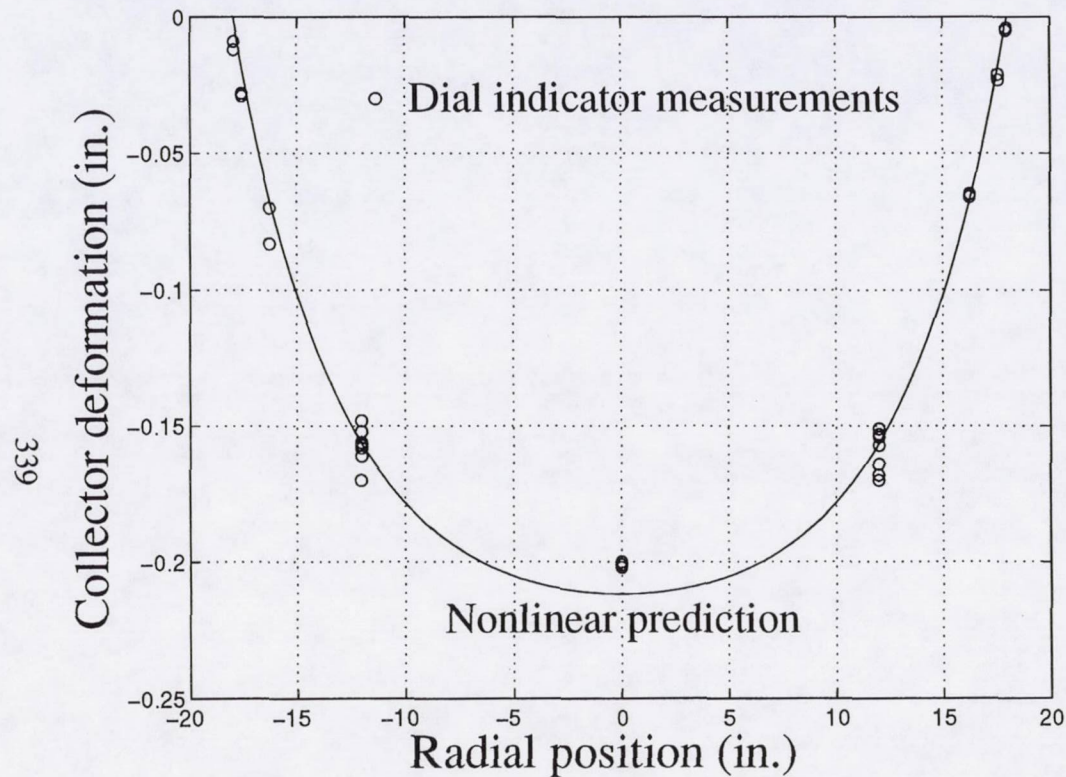
Pwr/Actuator: 5 watts

Austenitic start: 105°C

Slide 2

DWL

Experimental Results - Collector Performance



 Predicted diameters

Linear focal reduction: 32 in. $\longrightarrow$ 12 in.

Area focus ratio: $(32/12)^2 = 7.111$ (~ 7 suns)

Slide 3

Page intentionally left blank

OMIT THIS
PAGE

Poster Session

S33-71
61506
235120
y/p.

ACTIVE INTERIOR NOISE CONTROL STUDIES

J. Park, S. Veeramani, A. Sampath, B. Balachandran, and N. Wereley

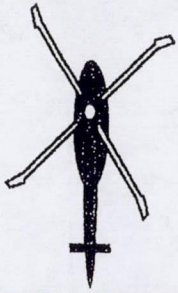
Smart Materials and Structures Research Center

A. James Clark School of Engineering

University of Maryland

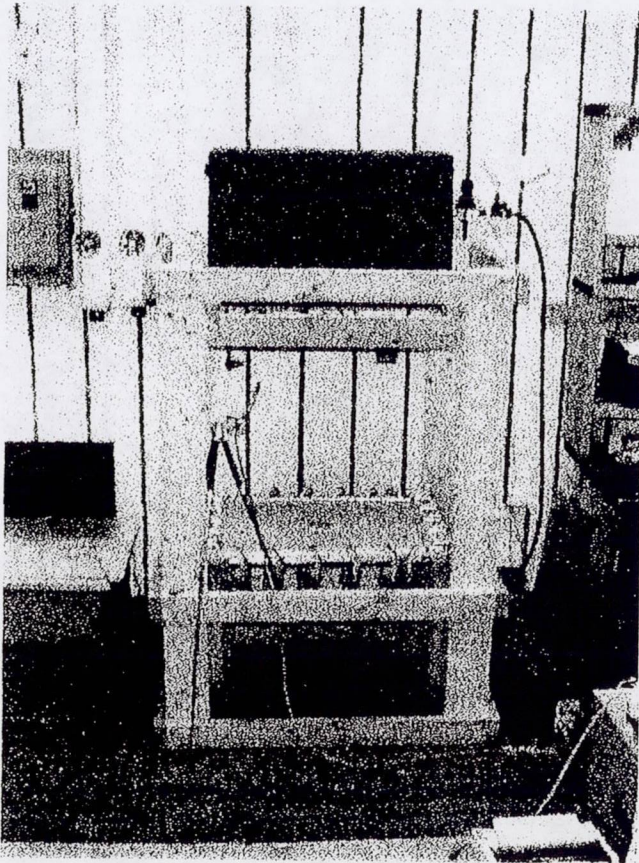
College Park, MD 20742-3035

Analytical and experimental investigations into the control of noise in the interior of a three-dimensional enclosure with a flexible boundary are presented. The rigid boundaries are constructed from acrylic material, and in the different cases considered the flexible boundary is constructed from either aluminum or composite material. Noise generated by an external speaker is transmitted into the enclosure through the flexible boundary and active control is realized by using Lead Zirconate Titanate (PZT) piezoelectric actuators bonded to the flexible boundary. Condenser microphones are used for noise measurements inside and outside the enclosure. Minimization schemes for global and local noise control in the presence of a harmonic disturbance are developed and discussed. In the experiments, analog feedforward control is implemented by using the harmonic disturbance as a reference signal.

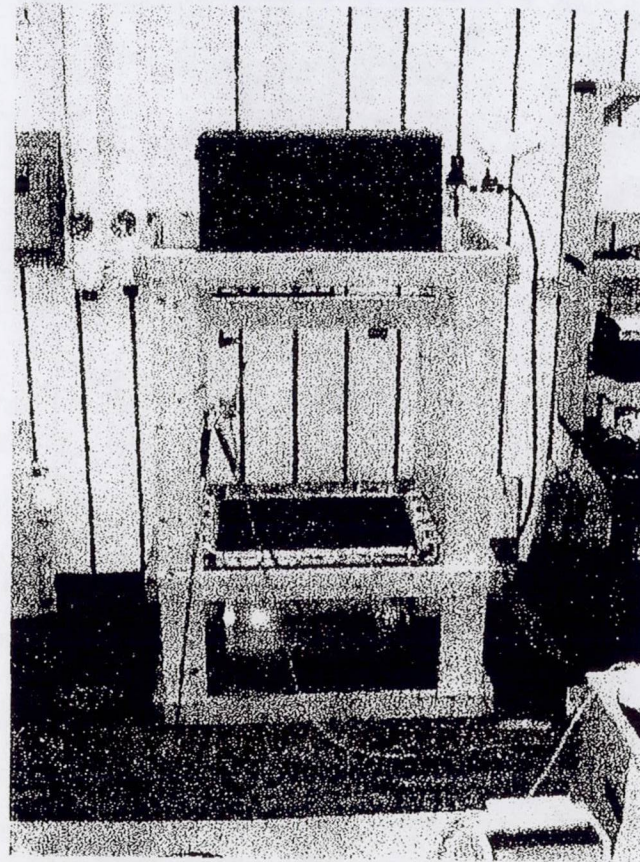


Active Interior Acoustics: Experimental Apparatus

Structural Test

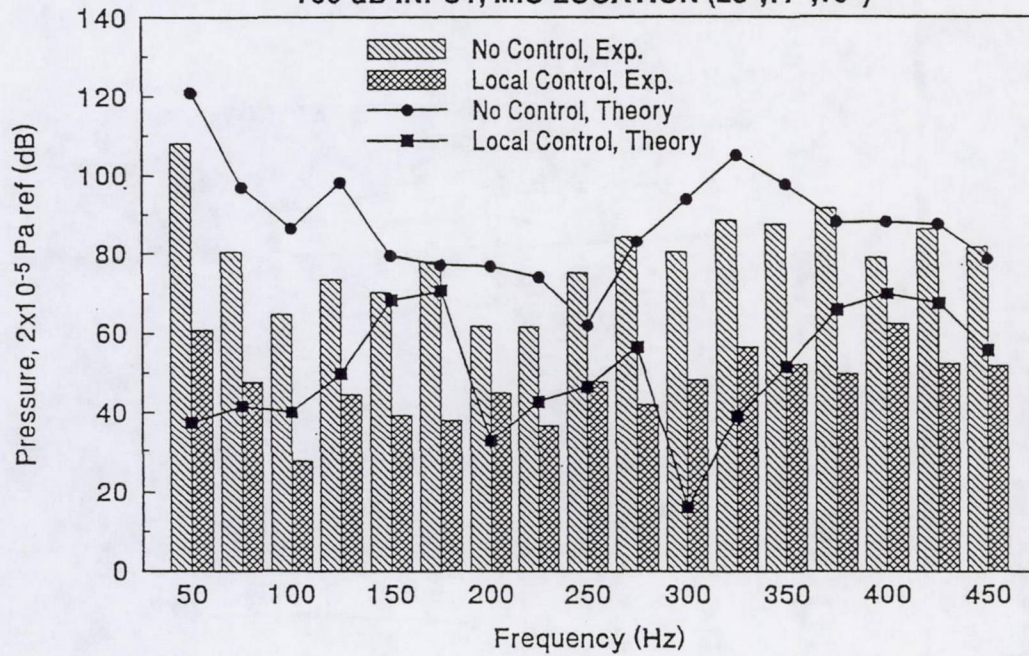


Acoustic Test

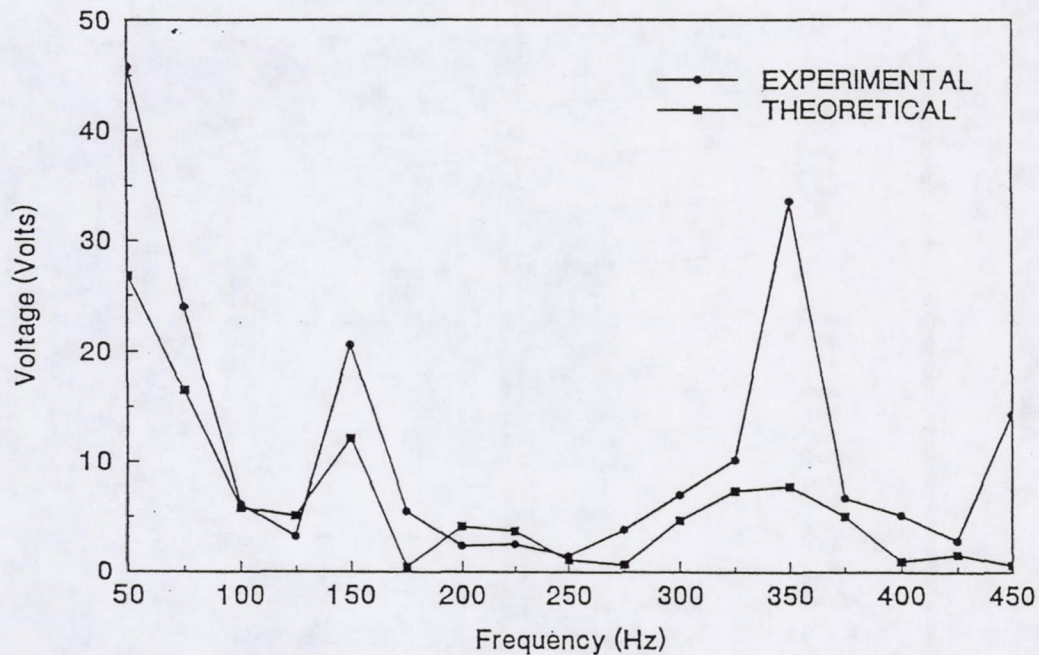


INTERIOR NOISE REDUCTION CLAMPED ALUMINUM PLATE

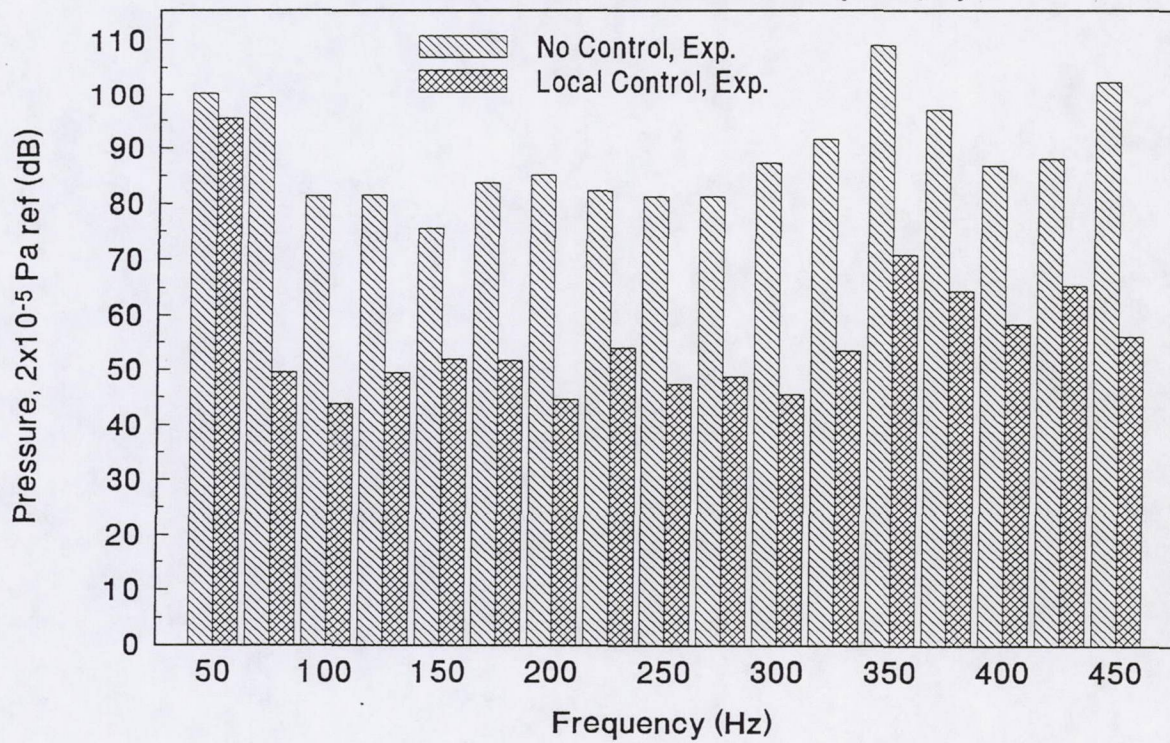
100 dB INPUT, MIC LOCATION (23",17",19")



OPTIMAL PZT VOLTAGE CLAMPED ALUMINUM PLATE MIC LOCATION (23",17",19")



**INTERIOR NOISE REDUCTION
CLAMPED GRAPHITE-EPOXY PLATE
100 dB INPUT, MIC LOCATION (1",1",1")**



Page intentionally left blank

ANALYSIS OF SENSORY/ACTIVE PIEZOELECTRIC COMPOSITE STRUCTURES IN THERMAL ENVIRONMENTS

Ho-Jun Lee and Dimitris A. Saravanos*

NASA Lewis Research Center
Structural Mechanics Branch
21000 Brookpark Rd., M.S. 49-8
Cleveland, Ohio 44135

534-35
61509
235101
6P.

INTRODUCTION

Although there has been extensive development of analytical methods for modeling the behavior of piezoelectric structures, only a limited amount of research^{1,2} has been performed concerning the implications of thermal effects on both the active and sensory response of smart structures. Thermal effects become important when the piezoelectric structure has to operate in either extremely hot or cold temperature environments. These extreme conditions may severely affect the response of smart structures in three distinct ways: (1) induction of thermal stresses due to differences in the coefficients of thermal expansion between the various composite plies and piezoelectric layers, (2) pyroelectric phenomena (i.e. changes in the electrical displacements arising from the coupled electrical and thermal behavior of the piezoelectric material), and (3) temperature dependence of the elastic, piezoelectric, and dielectric properties.

Consequently, the purpose of this paper is to extend the previously developed discrete layer formulation of Saravanos and Heyliger³ to account for the coupled mechanical, electrical, and thermal response in modern smart composite beams. The mechanics accounts for thermal effects which may arise in the elastic and piezoelectric media at the material level through the constitutive equations. The displacements, electric potentials, and temperatures are introduced as state variables, allowing them to be modeled as variable fields through the laminate thickness. This unified representation leads to an inherent capability to model both the active compensation of thermal distortions in smart structures and the resultant sensory voltage when thermal loads are applied. The corresponding finite element formulation is developed and numerical results demonstrate the ability to model both the active and sensory modes of composite beams with heterogeneous

plies with attached piezoelectric layers under thermal loadings.

FINITE ELEMENT FORMULATION

The finite element formulation for a composite piezoelectric beam is obtained by incorporating both a layerwise or through-the-thickness approximations along with the conventional in-plane finite element approximations to the state variables (displacements, electric potential, and temperature). By introducing these interpolated state variables into a combined variational form of the equation of motion and electrostatic equation, the following finite element matrix formulation can be obtained.

$$\begin{bmatrix} [M_{11}] & 0 & 0 \\ 0 & [M_{33}] & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \{\tilde{U}\} \\ \{\tilde{W}\} \\ \{\tilde{\Phi}\} \end{Bmatrix} + \begin{bmatrix} [K_{11}] & [K_{13}] & [K_{14}] \\ [K_{31}] & [K_{33}] & 0 \\ [K_{41}] & 0 & [K_{44}] \end{bmatrix} \begin{Bmatrix} \{U\} \\ \{W\} \\ \{\Phi\} \end{Bmatrix} = \begin{Bmatrix} \{F_1\} \\ \{F_3\} \\ \{Q\} \end{Bmatrix} + \begin{Bmatrix} \{F_{1,th}\} \\ 0 \\ \{Q_{th}\} \end{Bmatrix}$$

APPLICATIONS

Results from representative problems are presented in this section to evaluate the discrete layer formulation and to demonstrate the performance of simple sensory/active structures in thermal environments. Two different composite cantilever beam configurations are considered. For both cases, the beam is 25.4 cm (10 in) long and consists of various orientations of graphite/epoxy plies attached to piezoelectric layers, where each graphite/epoxy ply and piezoelectric layer has a thickness of 0.0127 cm (0.005 in). A total of 30

* Senior Research Associate, Ohio Aerospace Institute

equally spaced linear beam elements are modeled along the length of the beam, while one discrete layer is used through the thickness for each piezoelectric layer and for the graphite/epoxy laminate. The piezoelectric material used for this study is the commercially available piezoceramic APC 840 (American Piezo Ceramics, Inc.; Mackeyville, PA) while representative material properties of a graphite/epoxy composite were selected. The current study uses the constant through-the-thickness displacement beam theory, uses linear interpolation functions for both the through-the-thickness and in-plane approximations, and neglects the temperature dependence of material properties.

[0_s/p] Beam Under Uniform Thermal Load

The first beam considered is a [0_s/p] configuration, where p represents the piezoelectric layer, under a uniform thermal load of 100°C. The presence of the piezoelectric layer results in an unsymmetric laminate configuration, which induces thermal distortions under the thermal load.

Sensory Voltage. An important potential application of sensory structures is the monitoring of thermal distortions. In these applications, the displacement fields which arise under thermal loadings may be monitored through correlation with the measured voltages at the sensors. This capability is demonstrated in Figure 1, which shows the measured electric potential (from both the thermal strain and pyroelectric effects) on the top surface. The thermal strain sensory voltage accounts for the effects arising from the thermally induced deformations, while the pyroelectric voltage quantifies the effects that occur due to the variation in temperatures. This application demonstrates the capability to predict the different sensory voltages, which will provide the inferred essential feedback required for thermal distortion management of smart composite structures.

Thermal Distortion Management. The capability to actively compensate for thermal distortions is demonstrated in Figure 2 for the [0_s/p] beam. Through application of a voltage differential between the upper and lower surfaces of the piezoelectric layer, the converse piezoelectric effect can be utilized to compensate for the thermal displacements. As shown in the figure, the thermal displacement behavior of the beam can be completely altered depending on the value of the voltage differential. The thermal distortion can be eliminated by applying a voltage differential of 300

V, while a completely opposite curvature of the beam can be obtained by applying a voltage differential of 500 V. These results indicate the potential of piezoelectric structures to suppress thermally induced bending.

[p/0/90/±45]_s Beam Under Thermal Gradient

The present example considers multiple piezoelectric layers (to simultaneously take advantage of both the sensory and active behavior of piezoelectric materials), a more general lamination, [p/0/90/±45]_s, and a through-the-thickness linear thermal gradient (120°C on the top surface and 20°C on the bottom surface). Even though the beam has a symmetric laminate configuration including the piezoelectric layers, the applied thermal gradient produces a bending deflection in the beam.

Combined Sensory and Actuator Application. In this application, the upper piezoelectric layer is assumed to act as the sensor to monitor the induced electric potential, while the lower piezoelectric layer is used to actively compensate thermal deflections. Figure 3 shows the transverse deflections of the beam under applied voltages of 0 V, 100 V, and 200 V on the active (lower) piezoelectric layer. As shown in the figure, increasing the applied voltage reduces the thermally induced deflections from the reference state (0 V). In actual applications, a control loop would be established between the sensory and active layer, to monitor the sensory voltages and then to generate the appropriate active voltage which will minimize the thermal distortions. This capability is planned to be investigated in the near future.

REFERENCES

- 1 Rao, S.S. and Sunar, M., "Analysis of Distributed Thermopiezoelectric Sensors and Actuators in Advanced Intelligent Structures," AIAA Journal, Vol. 31, No. 7, pp. 1280-6, 1993.
- 2 Tzou, H.S. and Howard, R.V., "A Piezothermoelastic Thin Shell Theory Applied to Active Structures," Journal of Vibration and Acoustics, Vol. 116, pp. 295-302, 1994.
- 3 Saravanan, D.A. and Heyliger P.R., "Coupled Electromechanical Response of Composite Beams with Embedded Piezoelectric Sensors and Actuators," to appear in Journal of Intelligent Material Systems and Structures, also NASA CR 195313, 1994.

Figure 1

**[0₈/p] Beam - Uniform Thermal Load
Sensory Electric Potential**

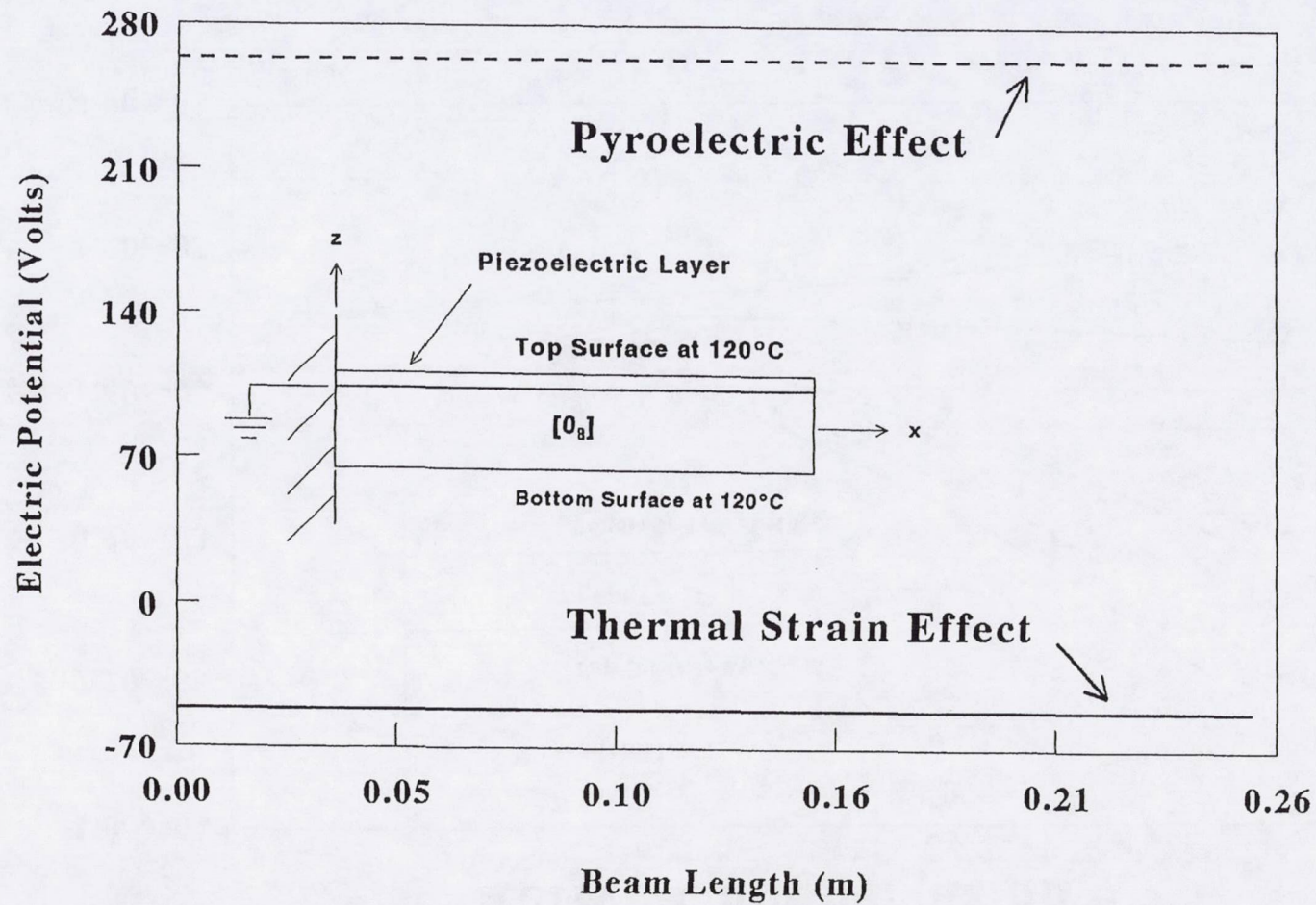


Figure 2

$[0_p/p]$ Beam - Uniform Thermal Load
Active Compensation

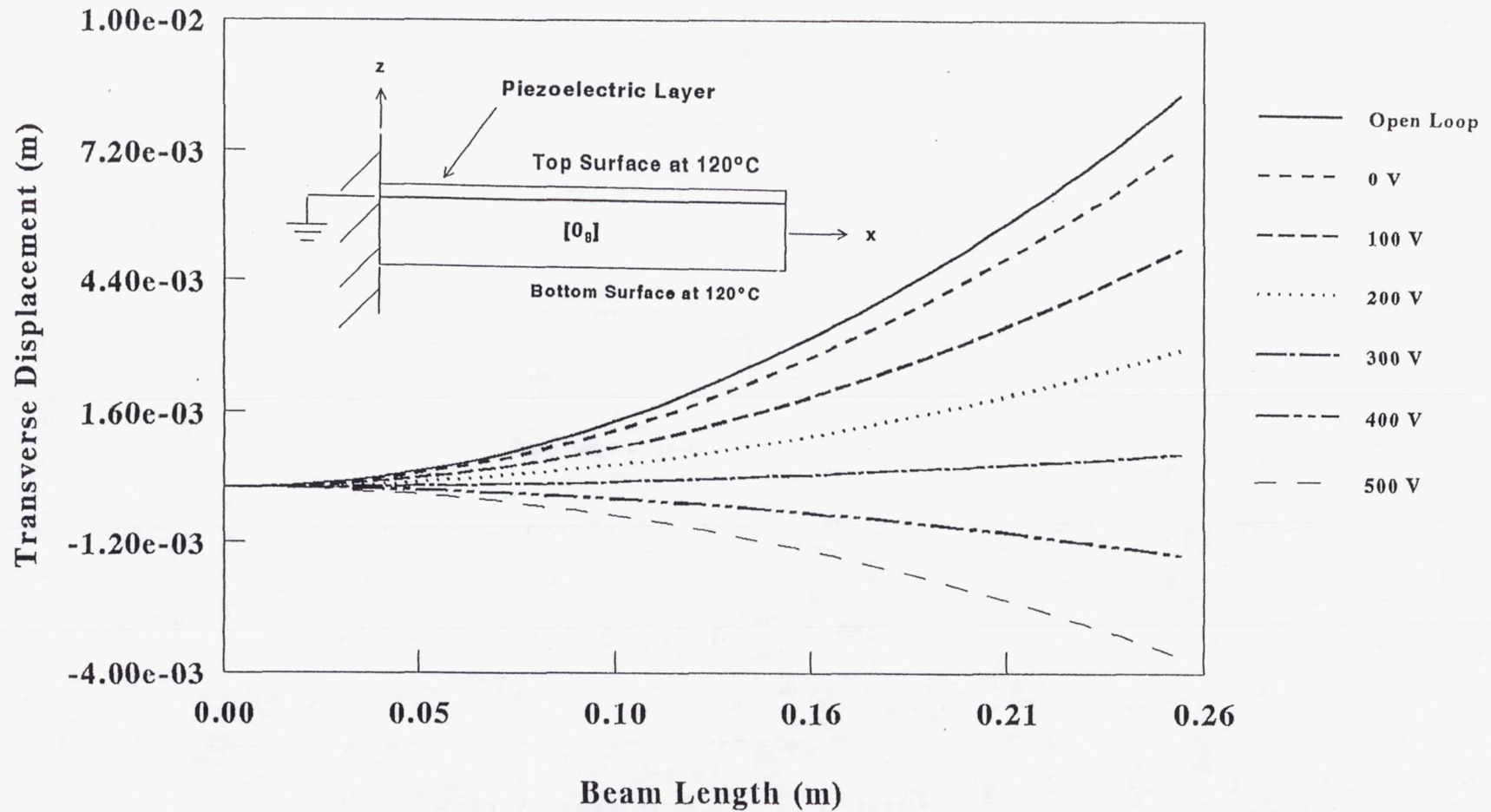
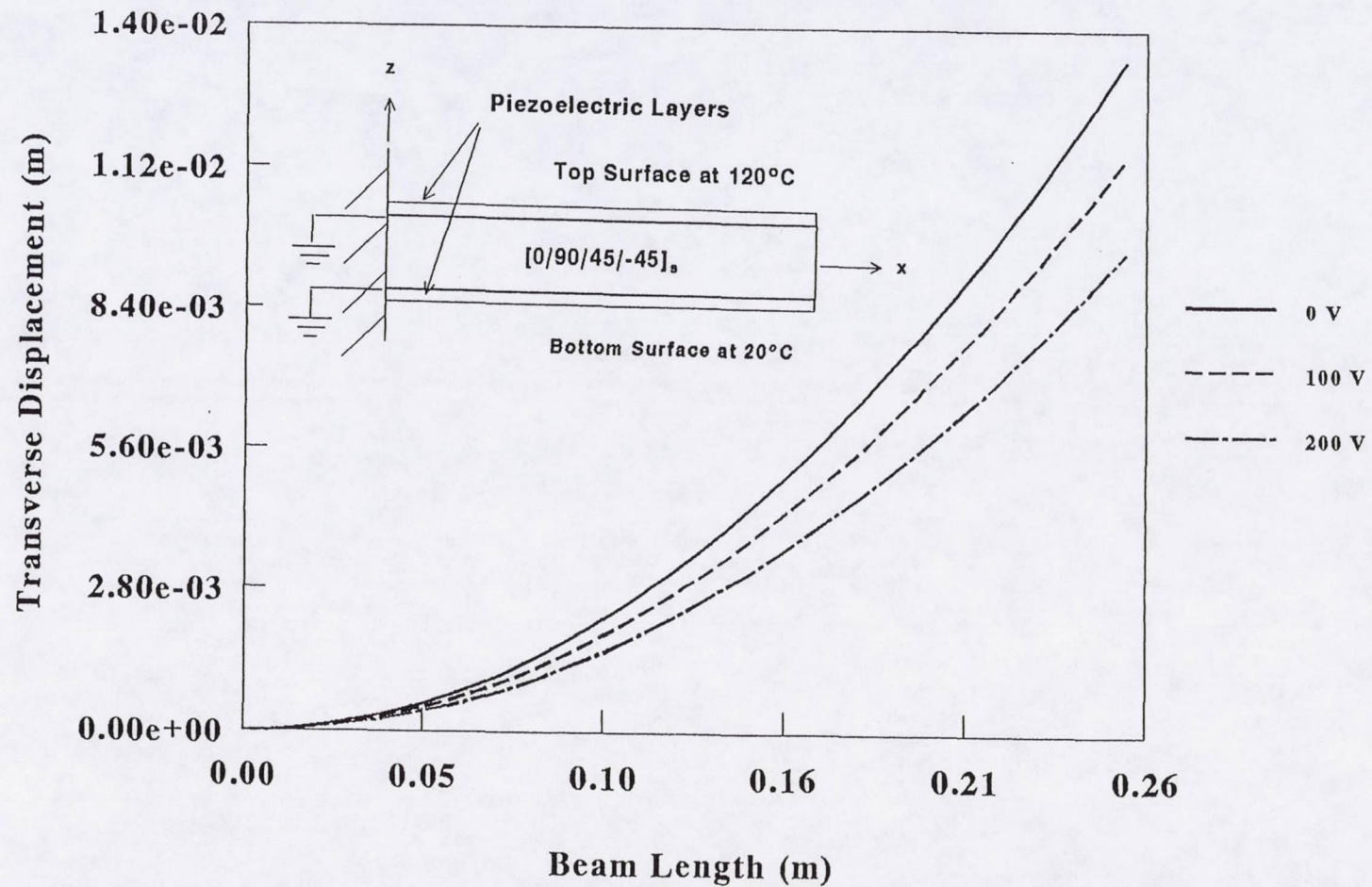


Figure 3

$[p/0/90/\pm 45]_s$ Beam-Thermal Gradient
Active Compensation



Page intentionally left blank

Characterization of the Dynamic Material Properties of Magnetostrictive Terfenol-D

by
Frederick T. Calkins
Alison B. Flatau
David L. Hall

535-27
61511
035122
4P

A major limitation in use of electromagnetic-magnetomechanical models for design of Terfenol-D actuators is the lack of reliable material property data for Terfenol-D. In particular data on the performance of Terfenol-D as employed in a transducer, operating under real world dynamic conditions is needed. To provide this information, Terfenol-D rod properties need to be measured under as run prestressed and magnetically biased states. Using a Terfenol-D actuator, the following properties can be measured and/or calculated: mechanical quality factor, speed of sound in the material, the resonant frequency, the anti-resonant frequency, two magnetic permeabilities (one at constant stress and one at constant strain), two Young's moduli (one at constant amplitude applied magnetic field and one at constant amplitude magnetic flux density in the material), the magnetomechanical coupling, and the axial strain coefficient. The development of the material properties measurements and calculations is based on the model of low signal, linear, magnetostriction from Clark [1], the linear transduction equations for a transducer from Hunt [2], and a one degree of freedom mechanical model of the transducer. The electrical impedance and admittance mobility loops are used to determine the resonant, anti-resonant, and half power point frequencies. The rest of the material properties indicated above can then be calculated using these frequencies, acceleration from an accelerometer mounted on the actuator arm, and readily measurable transducer and Terfenol-D rod parameters. The experimental procedure, developed at Iowa State University, is described in detail by Hall [3].

Mechanical Quality Factor Q

$$Q = \frac{f_R}{f_2 - f_1}$$

f_R is the resonant frequency of the transducer measured from the electrical impedance mobility loop; f_2 and f_1 are the one-half power points.

Axial strain coefficient q

$$q = \frac{\varepsilon}{H} \left[1 + \frac{k_{mps}}{k_m^H} \right]$$

q is the local slope of the strain versus applied field plot for a given constant stress. k_{mps} is the stiffness of the transducer prestress mechanism; k_m^H , the linear rod stiffness, is given by

$k_m^H = (2\pi f_R)^2 m_1 m_2 / (m_1 + m_2) - k_{mps}$ with mass of the transducer base m_1

and the effective mass of the Terfenol-D rod m_2 . The strain ε is calculated from the displacement at the free end of the rod, the measured acceleration divided by the squared circular frequency, and the length of the rod.

Magnetomechanical Coupling k^2

$$k^2 = \frac{k_{\text{eff}}^2}{k_m^2} \frac{(k_m^H + k_{\text{mps}})}{\left[k_m^H + \frac{k_{\text{eff}}^2 k_{\text{mps}}}{k_m^2} \right]}$$

The magnetomechanical coupling factor represents the fraction of magnetic energy that can be converted to mechanical energy per cycle and vice versa. The effective magnetomechanical coupling is calculated from the resonant and anti-resonant frequencies $k_{\text{eff}}^2 = 1 - (f_R/f_A)^2$. k_m^2 is the flux leakage measured for the transducer in use.

Young's modulus

$$E_Y^H = k_m^H L/A$$
$$E_Y^B = E_Y^H / (1 - k^2)$$

E_Y^H is the Young's modulus at constant applied field and E_Y^B is the Young's modulus at constant magnetic flux density in the material, for a Terfenol-D rod of length L and cross-sectional area A :

Magnetic Permeability

$$\mu^\sigma = \mu^\epsilon / k^2$$
$$\mu^\epsilon = \mu^\sigma (1 - k^2)$$

The magnetic permeability μ is the slope of the B versus H plot ($B = \mu H$). μ^ϵ is the permeability at constant strain, and μ^σ is the permeability at constant stress; the permeabilities, like the Young's Modulus, are related by the magnetomechanical coupling factor k^2 .

References

1. Clark, A.E., "Magnetostrictive rare earth Fe_2 compounds," ch. 7 of *Ferromagnetic Materials*, Vol. 1, E. P. Wohlfarth Editor, North-Holland Publishing Co., Amsterdam, pp. 531-589, 1980.
2. Hunt, F.V., "Electroacoustics: The Analysis of Transduction, and Its Historical Background," reprinted by the Acoustical Society of America, Woodbury, NY 1982.
3. Hall, D.L., "Dynamics and vibrations of magnetostrictive transducers," a PhD Dissertation, Iowa State University, Ames, IA 1994.

Acknowledgements

We would like to acknowledge the financial support of the NASA Graduate Student Research Program at the Langley Research Center (Dr. Richard Silcox technical advisor), and the NSF Research Initiation Award MSS-9212065 (Dynamic Systems and Controls Division).

Drive Level 30 mA

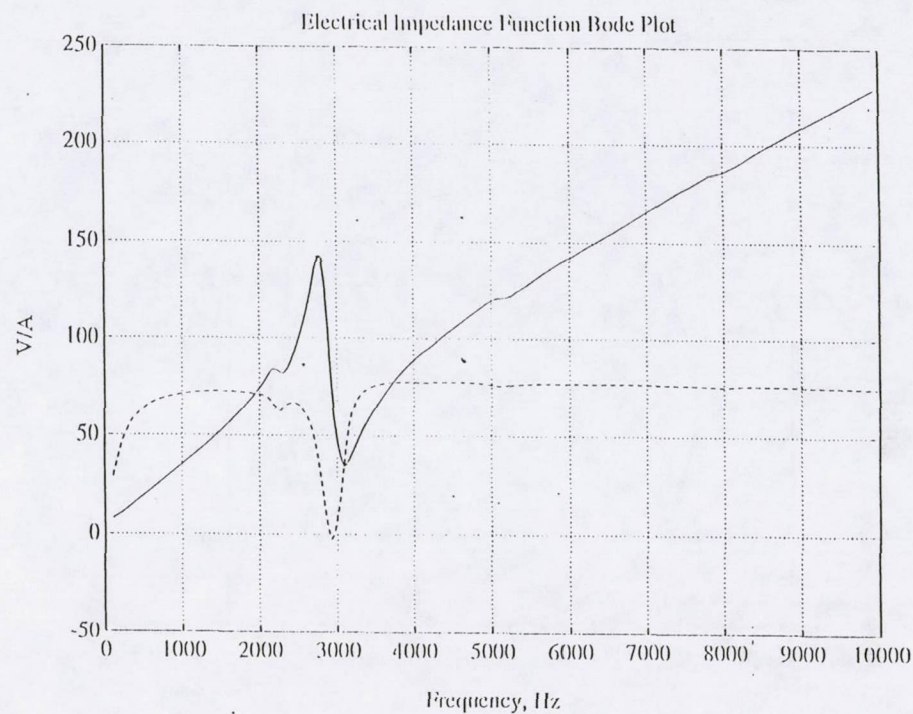
Terfenol-D Rod Properties

k^2	.256
α	$6.05(10^{-9})$ m/A
E_Y^H	$5.61(10^{10})$ N/m ²
E_Y^B	$7.54(10^{10})$ N/m ²
μ^σ	$8.021(10^{-6})$ Tm/A
μ^E	$5.967(10^{-6})$ Tm/A

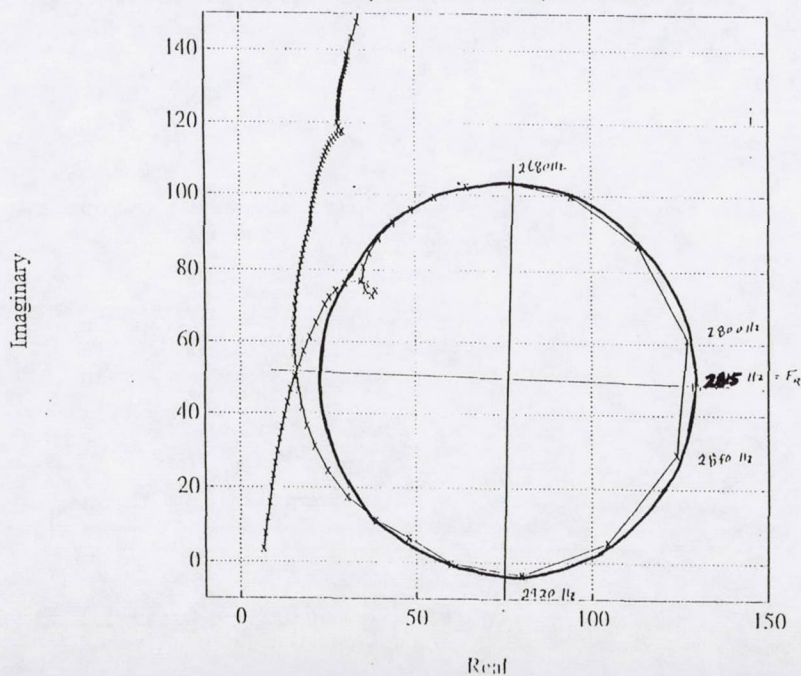
Terfenol-D Transducer Properties

Q	11.49
f_R	2815 Hz
f_A	3150 Hz

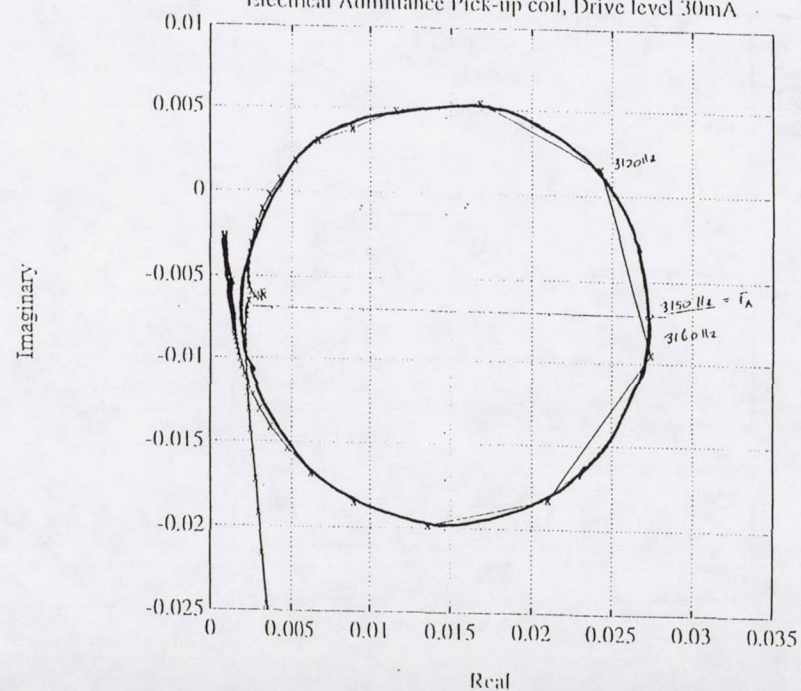
The electrical impedance bode plot, an impedance plot using the Nyquist format, and an admittance plot using the Nyquist format for the experimental data are shown below.



Electrical Impedance Drive coil, Drive level 30mA



Electrical Admittance Pick-up coil, Drive level 30mA



Drive Level 15 mA

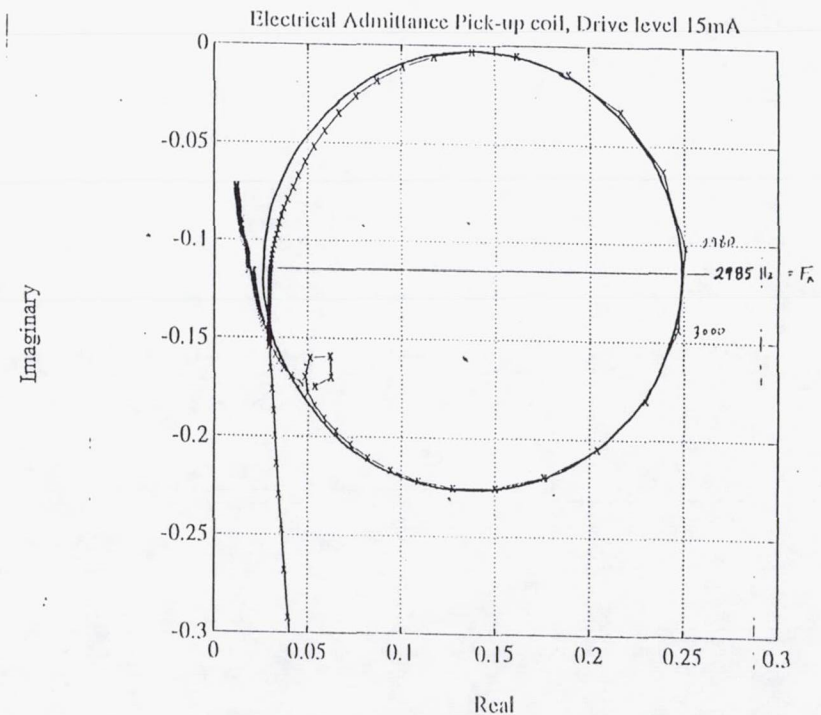
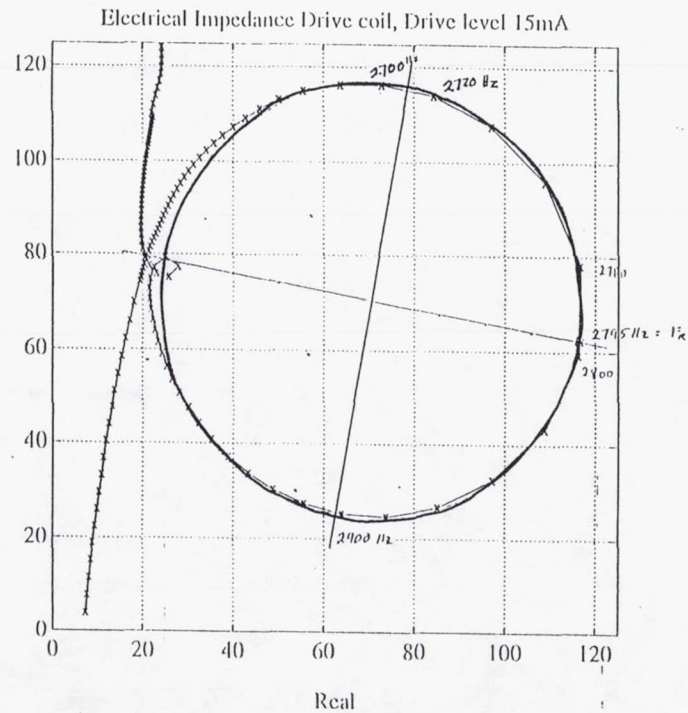
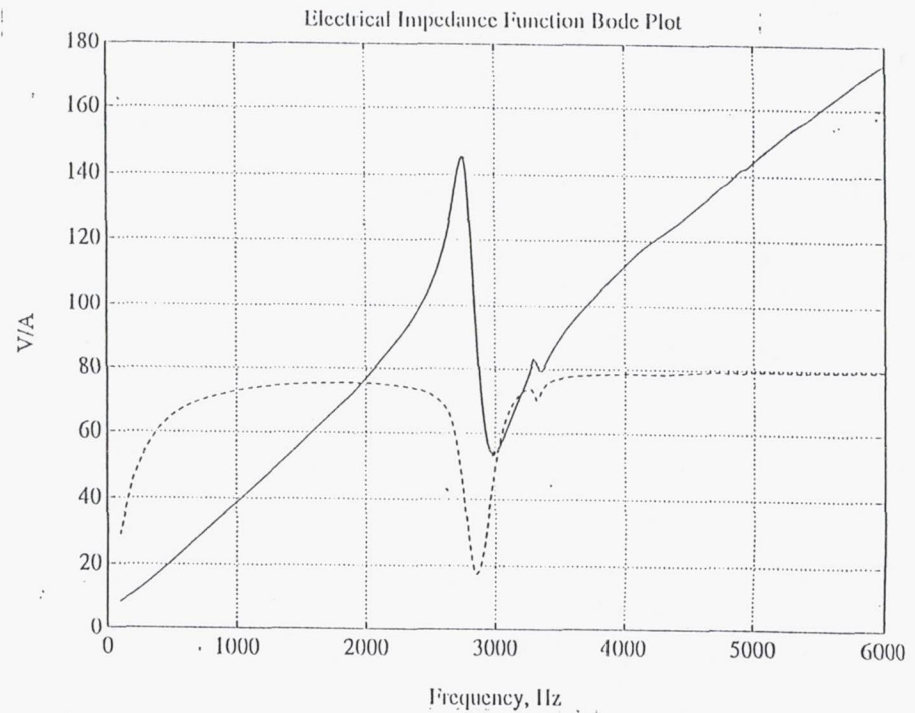
Terfenol-D Rod Properties

k^2	.157
α	$5.21(10^{-9})$ m/A
E_Y^H	$5.63(10^{10})$ N/m ²
E_Y^B	$6.68(10^{10})$ N/m ²
μ^σ	$9.74(10^{-6})$ Tm/A
μ^ϵ	$8.21(10^{-6})$ Tm/A

Terfenol-D Transducer Properties

Q	14.33
f_R	2795 Hz
f_A	2985 Hz

The electrical impedance bode plot, an impedance plot using the Nyquist format, and an admittance plot using the Nyquist format for the experimental data are shown below.



CONSTITUTIVE MODELS FOR SHAPE MEMORY ALLOY POLYCRYSTALS

R.J. Comstock, Jr., M. Somerday and J.A. Wert
Department of Materials Science and Engineering,
University of Virginia, Charlottesville, VA 22903

Introduction

Shape memory alloys (SMA) exhibiting the superelastic or one-way effects can produce large recoverable strains upon application of a stress. In single crystals this stress and resulting strain are very orientation dependent. Fig. 1 shows experimental stress/strain curves by Enami *et al.*^[1] for a Ni-Al single crystal for various loading orientations. Also shown are model predictions by Buchheit and Wert^[2]; the open and closed circles indicate recoverable strains obtained at various stages in the transformation process. Because of the strong orientation dependence of shape memory properties, crystallographic texture can be expected to play an important role in the mechanical behavior of polycrystalline SMA. It is desirable to formulate a constitutive model to better understand and exploit the unique properties of SMA.

Models

Buchheit and Wert^[3] have shown that SMA can be modeled using elements of plasticity theory. Slip occurs on a slip plane in the slip direction, similarly twinning occurs on the twin plane in the shear direction. The stress-induced thermoelastic martensitic transformation in SMA occurs on a habit plane in a shear direction. Each habit plane/shear direction combination is termed a transformation shear system. This, as well as the magnitude of shear, can be calculated for shape memory alloys using the Phenomenological Theory of Martensite Crystallography (PTMC)^[4]. The required inputs of the PTMC are the lattice parameters of the austenite and martensite crystal structures, the lattice correspondences, and the lattice invariant shear plane. The output is a set of 24 equivalent transformation shear systems for the SMA being modeled.

Unconstrained Single Crystal Model

The unconstrained single crystal model considers application of a prescribed stress state to a single crystal, for which the strain response is unrestricted. Such models use the Generalized Schmid's Law to resolve the applied stress on the habit plane and in the shear direction:

$$m_{ij}^s = \mathbf{n}_1^{(s)} \cdot \mathbf{a}_i \mathbf{n}_2^{(s)} \cdot \mathbf{a}_j \quad [1]$$

where $\mathbf{n}_1^{(s)}$ and $\mathbf{n}_2^{(s)}$ are the habit plane normal and shear direction for the transformation system (s), $\mathbf{a}_i$ and $\mathbf{a}_j$ are the basis vectors associated with the austenite crystal, and m_{ij}^s is the tensor transformation matrix that resolves the stress components (σ_{ij}) on the habit plane in the shear direction. Expressing σ_{ij} in the same coordinate system used for $\mathbf{n}_k^{(s)}$ and $\mathbf{a}_k$, the criterion for shear on system s is:

$$\sigma_{ij} m_{ij}^s = \tau_t \quad [2]$$

where τ_t is the critical resolved transformation stress. For a specific crystal orientation and loading path, the preferred transformation shear system is that having the largest $\sigma_{ij}m_{ij}$ product^[3,5].

Constrained Single Crystal Model

The constrained single crystal model considers imposition of a strain increment on the material and seeks to determine the stress components necessary to induce this strain increment. Imposing a strain increment on a crystal and assuming constant volume requires the activation of a minimum of 5 transformation shear systems to accommodate the 5 independent strain components. Positions in stress space where 5 or more transformation shear systems intersect are termed *stress corners*^[5].

The stress corner that is activated for an imposed strain state is determined by the Bishop-Hill principle of maximum work:

$$\sigma_{ij}^* d\epsilon_{ij} \geq \sigma_{ij} d\epsilon_{ij} \quad [3]$$

where σ_{ij}^* are the stress components of the corner yielding the maximum work of deformation and σ_{ij} are the components of an arbitrary corner. The components σ_{ij}^* must be imposed on the crystal to produce the prescribed strain increment^[6].

Unlike slip, the martensitic transformation yields a magnitude of shear (γ_t) which is an output of the PTMC and is characteristic of the SMA. The magnitude of strain (ϵ_{ij}) is then found using a work-of-transformation argument:

$$W_t = \tau_t \gamma_t = \sigma_{ij}^* \epsilon_{ij} \quad [4]$$

where W_t is the work per unit volume required to fully transform austenite to martensite.

Lower-Bound Polycrystalline Model

Texture measurement allows representation of the polycrystal as a set of weighted grains numbering about 2000^[7]. Each grain is modeled as an unconstrained single crystal with the stress state on each grain equal to the stress state on the sample. The stress is in equilibrium, however, compatibility conditions are not met. As proportional loading increases, the grain requiring the lowest work of transformation is modeled to activate first. The applied stress at which this occurs and resulting strain state can be calculated. This can be done for all 2000 grains. The stress vs. the weighted strain for each grain can be plotted producing a stress/strain curve.

Upper-Bound Polycrystalline Model

Upper-bound polycrystalline models for the case of slip impose the strain of the sample on each grain. In this case, compatibility conditions are met, but stress is not in equilibrium. The upper-bound polycrystalline model for SMA satisfies the compatibility requirement at low strains, however, due to the fixed strain associated with complete transformation, intergranular compatibility cannot be met at intermediate to large strains.

A stress/strain curve can be plotted in the same manner as discussed for the lower-bound polycrystalline model. The single difference is the conversion of the corner stress state to an applied sample stress by the following work argument:

$$W_t = \sigma_{ij}^* \epsilon_{ij} = \sigma_{ij}^A \epsilon_{ij} \quad [5]$$

where the applied stress is σ_{ij}^A .

Polycrystalline Model Results

Texture measurements for 2.0 mm diameter NiTi wire, obtained from Raychem, enabled normalized stress vs. strain upper- and lower-bound curves to be generated for stress induced martensite. The results are shown in Fig. 2.

Current capabilities allow modeling of NiTi, Cu-Al-Ni, Ni-Al, AuCd, Cu-Zn, Cu-Zn-Al, and Cu-Zn-Ga polycrystalline SMA. Model evaluation and refinement will be the subject of future work.

Acknowledgments

The authors acknowledge T.E. Buchheit, currently at Sandia National Lab., as a major contributor to this work. Support was provided by the National Science Foundation under Grant No. 3 DMR-9924487.

References

1. K. Enami, V.V. Martynov, T. Tomie, L.G. Khandros, and S. Nenno: *Trans. JIM*, 1981, vol. 22, pp. 357-66.
2. T.E. Buchheit and J.A. Wert: *Metall. Trans. A*, 1994, submitted for publication.
3. T.E. Buchheit and J.A. Wert: *Metall. Trans. A*, 1994, vol. 25, pp. 2383-9.
4. D.S. Lieberman, M.S. Weschler, and T.A. Read: *J. Appl. Phys.*, 1955, vol. 26, pp. 473-84.
5. U.F. Kocks, *Metall. Trans.*, 1970, vol. 1, pp. 1121-43.
6. J.F.W. Bishop and R. Hill: *Phil. Mag.*, 1951, vol. 42, pp. 414-427.
7. U.F. Kocks, J.S. Kallend, and A.C. Biondo: in *Proc. 9th Int. Conf. Text. Mat.*, Avignon, France, September 17-21, 1990.

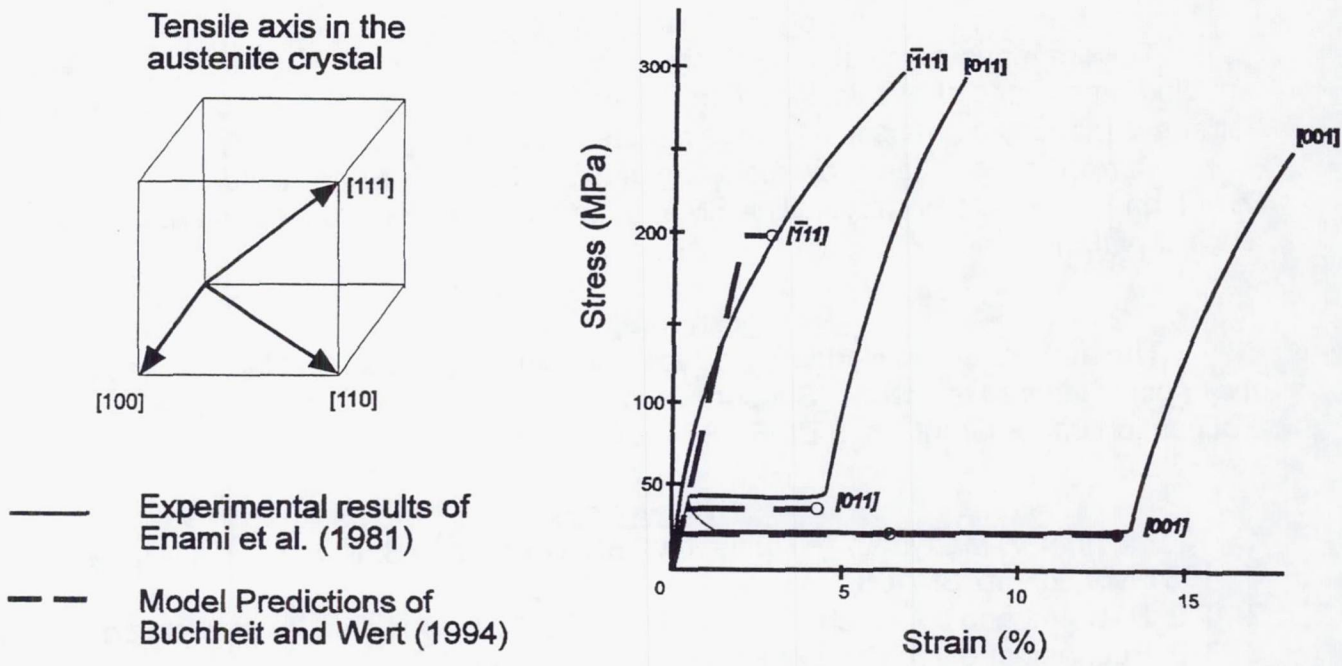


Fig. 1 Anisotropy of single crystal Ni-Al.

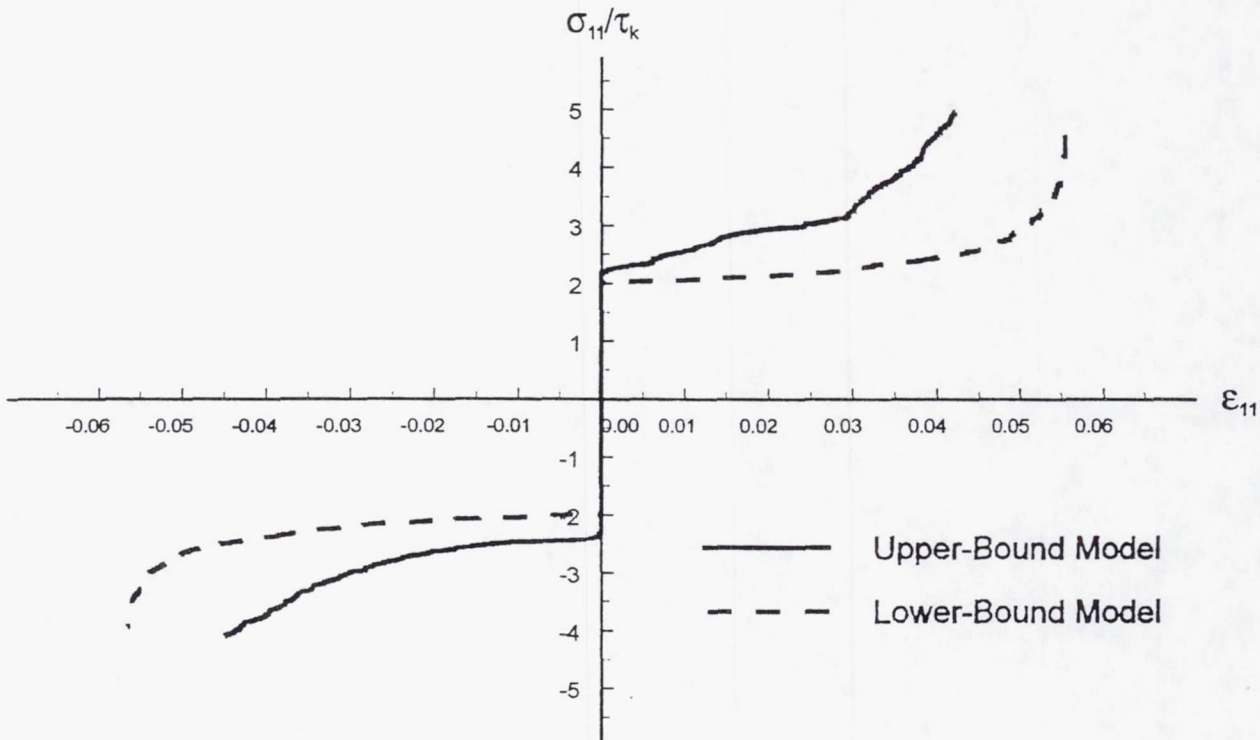


Fig. 2 Polycrystal results for a NiTi 2.0 mm diameter wire under uniaxial loading.

837-33
ABS ONLY
61515

Design of a Mode Conversion Ultrasonic Motor for Position Control

Ronan Le Letty, Philippe Bouchilloux*, Frank Claeysen, and Nicolas Lhermet
Cedrat Recherche, 10 Chemin du Pré Carré
ZIRST 4301, F38943 Meylan Cedex, France

235124

1P.

The many useful characteristics of ultrasonic motors, such as high holding torques, and high torque at low speeds, have made them the subject of increasing interest. In addition, several of their characteristics make them attractive for aerospace applications: they have a torque to weight ratio, and they require neither gearing mechanisms nor lubrication. Moreover, they create negligible magnetic fields, and conversely, they are not affected by external magnetic fields. Ultrasonic motors based on bolt-tightened structures offer simplicity and high stress capability. They use the inverse piezoelectric effect in the stator to produce vibrational energy, which is transferred to the rotor by friction.

We designed a bolt-tightened ultrasonic motor using numerical modelling tools (finite element and electromechanical circuit analyses), creating an equivalent circuit model that takes into account the electromechanical energy conversion in the stator and the contact between the stator and the rotor. Analysis of the circuit gives insight into the behavior of the motor and allows its performance to be calculated. Two prototypes of the motor were built; their transient responses and other quantities, such as starting torque, were measured.

In this paper, we discuss the numerical and the experimental results, and demonstrate the usefulness of numerical analysis in designing ultrasonic motors and estimating their performance.

*Magsoft Corp., 1223 Peoples Avenue, Troy, NY 12180

Page intentionally left blank

538-24
61519
235125

5 P.

**Detection of Delamination in Composite Beams Using Broadband
Acoustic Emission Signatures**

A.C. Okafor, K. Chandrashekhara, Y.P. Jiang

Department of Mechanical and Aerospace Engineering and
Engineering Mechanics
University of Missouri-Rolla
Rolla, Missouri 65401

Summary

Advanced composites have been shown to be very attractive in aerospace and automotive industries because of some inherent advantages over conventional metal materials. They may include excellent mechanical strength/weight ratio. However, the mechanical properties may degrade significantly by different failure modes associated with composites. Delamination in composite laminate is one of the common failure modes and is of particular interest because it may cause catastrophic failure of the composite structure. The ability to detect the occurrence and location of a delamination is therefore important in predicting and preventing catastrophic failures of composite structures. Delamination in composite structure may be caused by imperfections introduced during the manufacturing process or by impact loads by foreign objects during the operational life. There are some nondestructive evaluation methods to detect delamination in composite structures such as x-radiography, ultrasonic testing, and thermal/infrared inspection. These methods are expensive and hard to use for on line detection. Acoustic emission testing can monitor the material under test even under the presence of noise generated under load. It has been used extensively in proof-testing of fiberglass pressure vessels and beams. In the present work, experimental studies are conducted to investigate the use of broadband acoustic emission signatures to detect delaminations in composite beams. Glass/epoxy beam specimens with full width, prescribed delamination sizes of 2 inches and 4 inches are investigated. The prescribed delamination is produced by inserting Teflon film between laminae during the fabrication of composite laminate. The objectives of this research is to develop a method for predicting delamination size and location in laminated composite beams by combining smart materials concept and broadband AE analysis techniques. More specifically, a piezoceramic (PZT) patch is bonded on the surface of composite beams and used as a pulser. The piezoceramic patch simulates the AE wave source as a 3 cycles, 50KHz, burst sine wave. One broadband AE sensor is fixed near the PZT patch to measure the AE wave near the AE source. A second broadband AE sensor, which is used as a receiver, is scanned along the composite beams at 0.25 inch step to measure propagation of AE wave along the composite beams. The experimental setup is shown in figure 1. The acquired AE waveform

is digitized and processed. Signal strength, signal energy, cross-correlation of AE waveforms, and tracking of specific cycle of AE waveform are used to detect delamination size and location. Figure 2 shows samples of AE wave forms as the AE receiver is scanned along the beam with 2 inch delamination. Figures 3, 4 and 5 show the computed energy versus scanned distance for a perfect beam, beam with 4 inch and 6 inch delamination respectively. From the results, the following conclusions can be made: (1). For the fixed excitation frequency investigated, AE waves have been shown to be sensitive to delaminations in glass/epoxy composite beams. (2). For a perfect beam, the AE amplitude, energy, and signal strength, decrease as the AE wave propagates along the beam. This phenomena is observed by scanning AE sensor (receiver) along the beam. (3). For a delaminated beam, the AE amplitude, energy and signal strength decrease significantly to a minimum (almost zero) at the delamination area and then increase after the delamination area. But this increase does not reach the original signal level and shape as before the delamination zone. This knowledge is very useful for detecting delamination size and location. (4). As the AE waves propagate through delamination in the composite beams, the attenuation of the signal is dependent on delamination size. The larger the delamination size, the higher the attenuation. If the delamination size is too large, the signal will be severely attenuated and the signal strength method may not successfully determine delamination size and location. (5). Similar pattern were observed with cross-correlation function measurements. The peaks of the cross-correlation functions decrease as the receiver is moved away from the AE reference signal (source). The decrease is more significant over the delamination area. (6). Delaminated beams produce more peaks in the cross-correlation functions than non-delaminated beams. This multiple peaks might be due to reflection from the delaminations.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research under grant # ONR N00014-94-1-1200 with Dr. Thomas M. McKenna as the Technical Monitor. Partial supports from the Missouri Department of Economic Development, the University of Missouri Research Board, and the University of Missouri-Rolla are gratefully acknowledged.

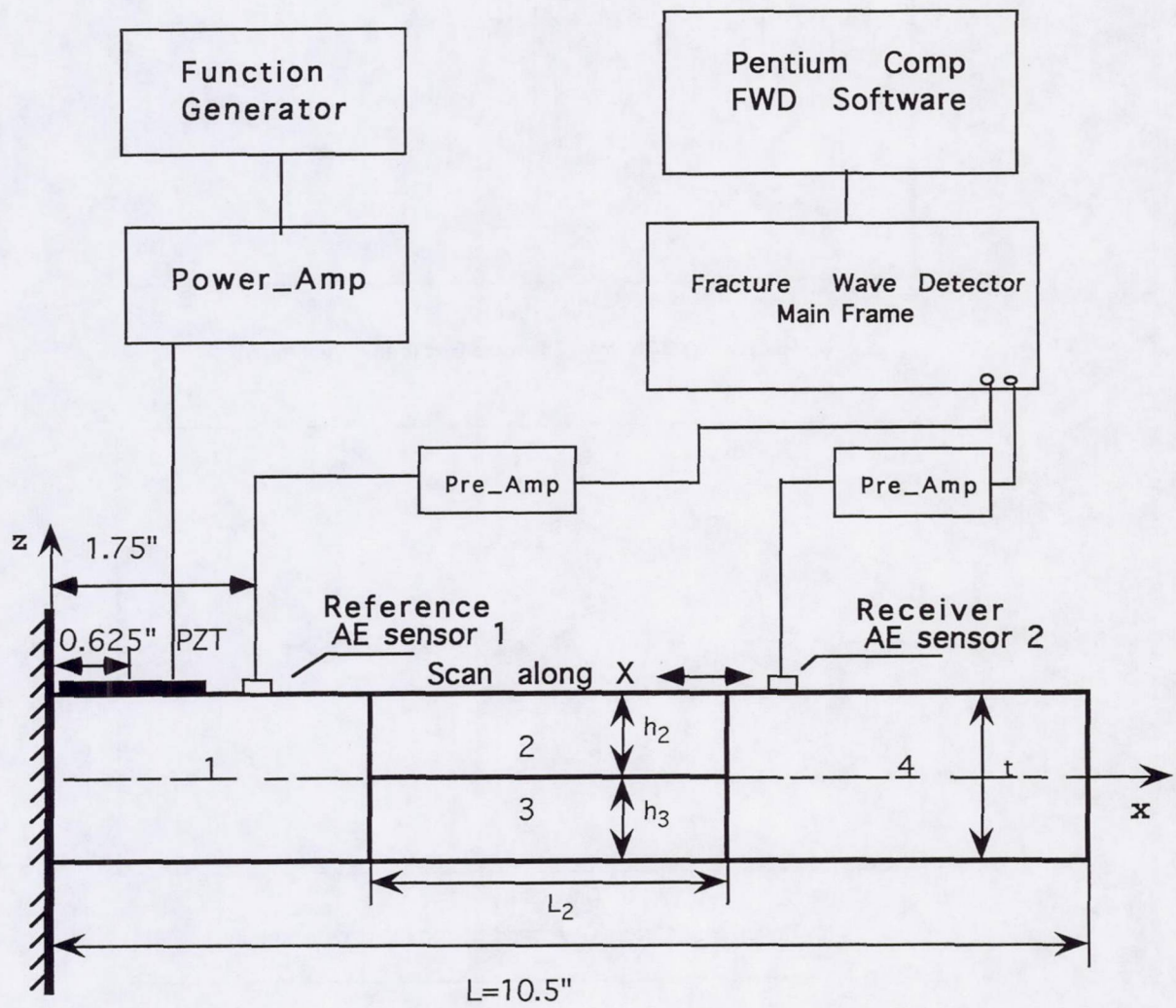
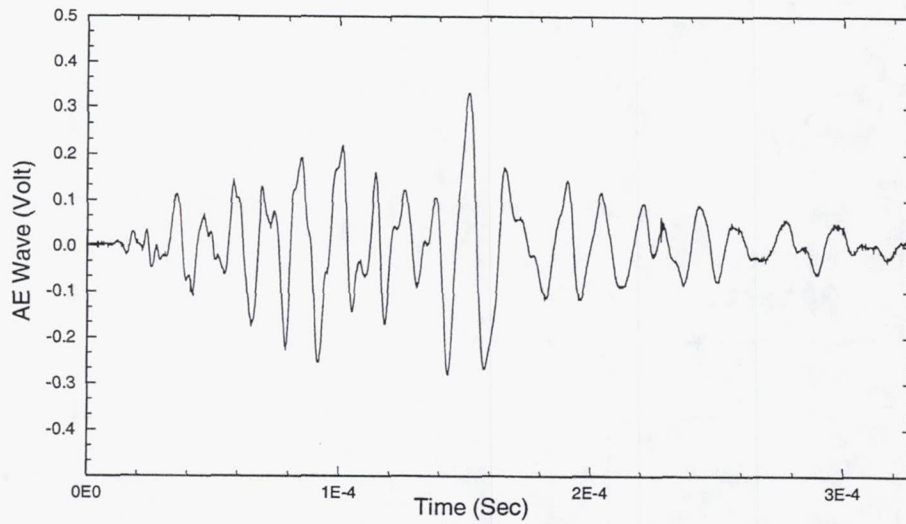
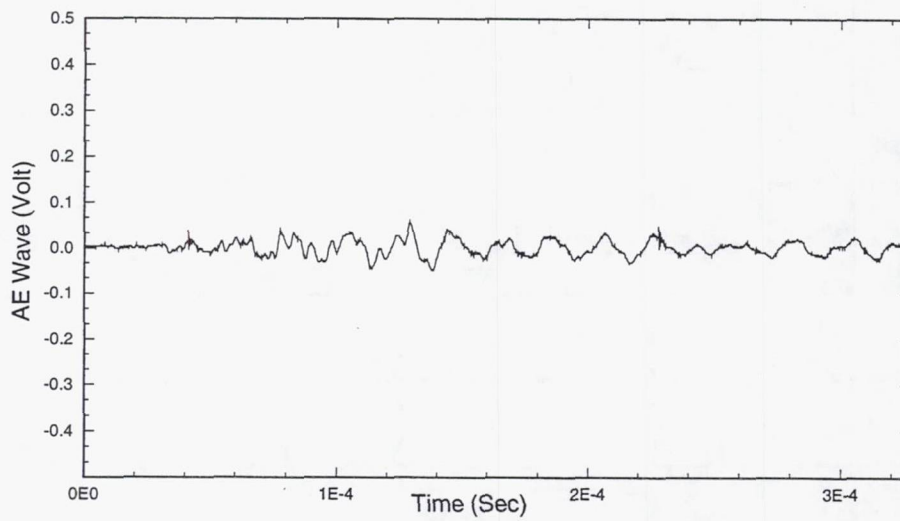


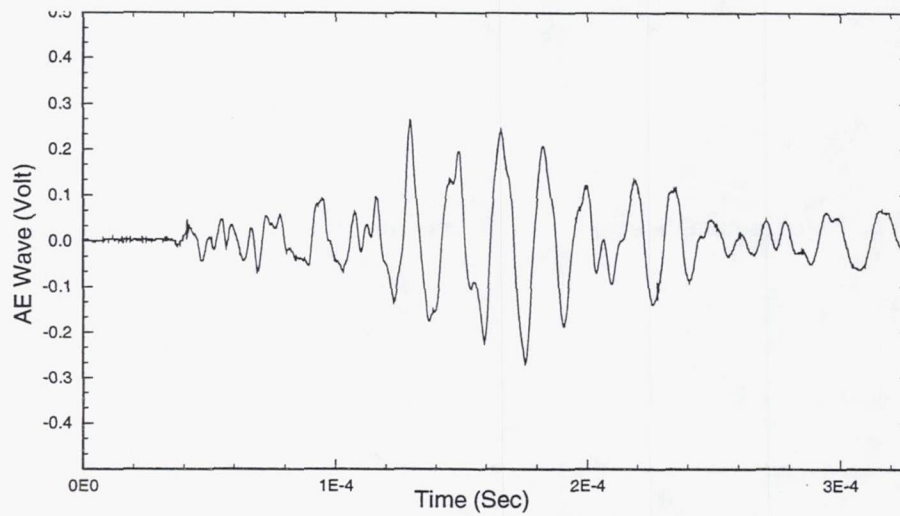
Figure 1. Experimental Set-up for AE Testing of Delamination in Composite Beams



(a) Receiver at 2.75" from Clamped End (before delamination)



(b) Receiver at 4" from Clamped End (on top of delamination)



(c) Receiver at 6" from Clamped End (after delamination)

Figure 2. Series of AE Waveforms as Receiver is Scanned over 2" Delamination Beam

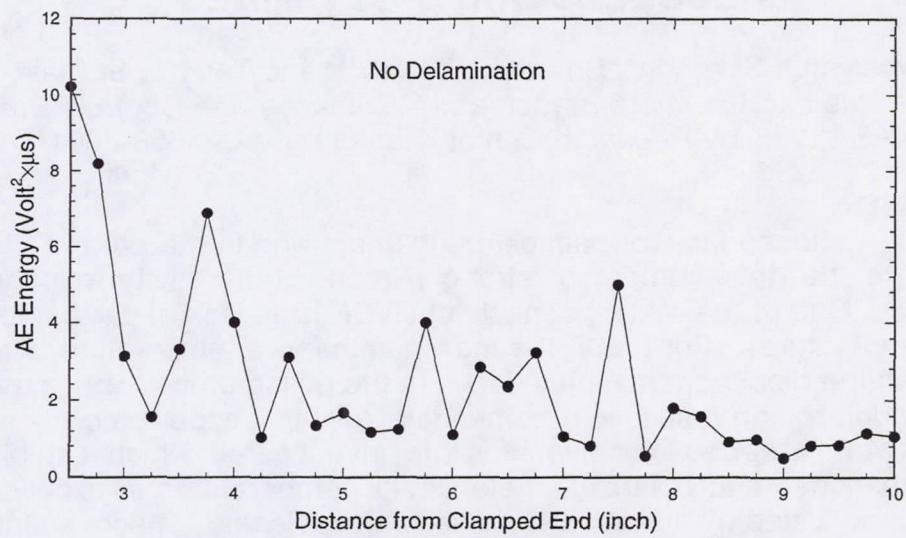


Figure 3. AE Energy Versus Distance from Clamped End (perfect beam)

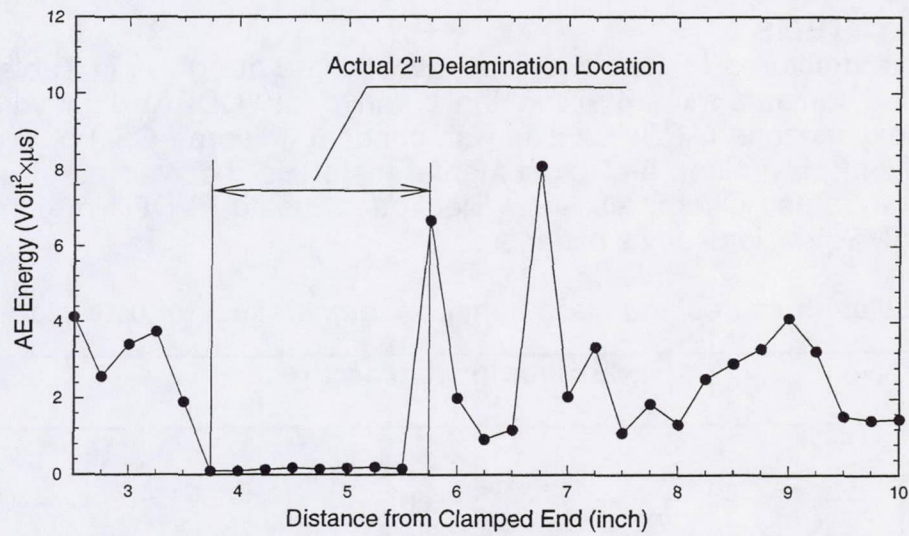


Figure 4. AE Energy Versus Distance from Clamped End (2" delamination beam)

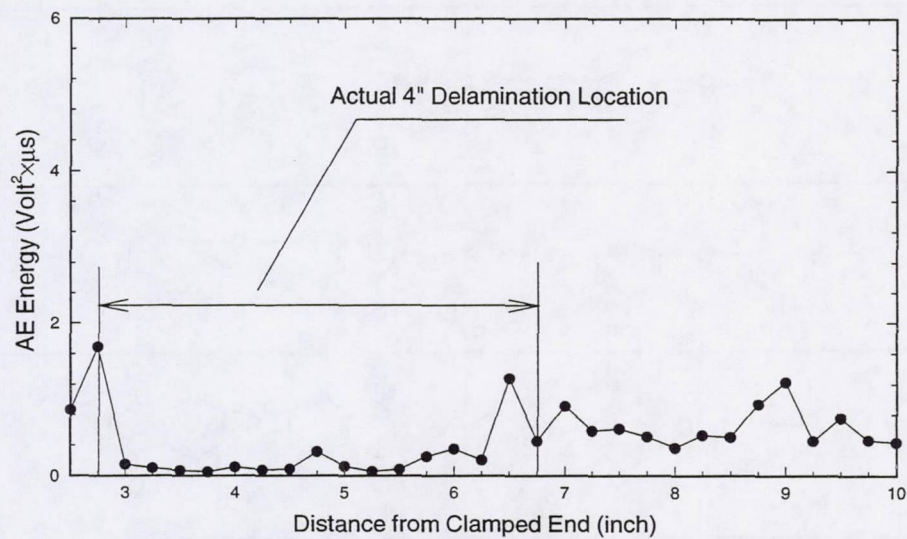


Figure 5. AE Energy Versus Distance from Clamped End (4" delamination beam)

DEVELOPMENT OF HIGH PERFORMANCE PIEZOELECTRIC POLYIMIDES

Joycelyn O. Simpson*, Sharon S. Welch**, and Terry L. St.Clair*

*Composites and Polymers Branch and **Guidance and Controls Branch
NASA Langley Research Center, Hampton, VA 23666-0001.

INTRODUCTION

Kawai's [1] pioneering work almost thirty years ago in the area of piezoelectric polymers led to the development of strong piezoelectric activity in polyvinylidene fluoride (PVDF). One of the limiting aspects of PVDF is its lack of piezoelectric activity at elevated temperatures. For PVDF the maximum service temperature is about 80°C [2] above which the dipole orientation induced in the poling process begins to reverse. This dipole randomization results in a tremendous loss in piezoelectricity.

In this work a series of polyimides are investigated which exhibit a strong piezoelectric response and polarization stability at temperatures in excess of 100°C. This work was motivated by the need to develop piezoelectric sensors suitable for use in high temperature aerospace applications.

POLYMER SYSTEMS

Molecular structures of the polyimides investigated are given in Table 1. Each of the polyimides contains the 4,4' oxydiphthalic anhydride (ODPA) dianhydride and a bis-aminophenoxybenzene (APB) diamine with pendant trifluoro (-CF₃) or cyano (-CN) groups. All of the polyimides are experimental materials received as free standing films from Mitsui Toatsu Chemicals, Inc. Electroded, poled PVDF film commercially obtained from AMP, Inc. is used as a standard.

Table 1. Molecular structures and glass transition temperatures of polyimides studied.

Name	Molecular Structure	T _g (°C)
(β-CF ₃)-APB/ ODPA		175
(α,δ-CF ₃)- APB/ODPA		176
(α,β,δ-CF ₃)- APB/ODPA		180
(β-CN)- APB/ODPA		220

ELECTRODING AND POLING

Polymers are poled using the conventional direct voltage poling procedure. Each sample is heated to within 10°C of its T_g by immersion in a heated silicone oil bath. A DC electric field (E_p) in the range of 100 to 125 MV/m is applied to polarize each sample. While maintaining E_p constant, the temperature is lowered to room temperature to retain the induced polarization.

RESULTS AND DISCUSSION

The piezoelectric g_{33} constants were calculated for each of the samples from the measured ratios of voltage output to force input at a 100 MHz excitation frequency. Figure 1 is a plot of the calculated g_{33} constants for $(\alpha,\delta\text{-CF}_3)\text{-APB/ODPA}$, $(\alpha,\beta,\delta\text{-CF}_3)\text{-APB/ODPA}$, $(\beta\text{-CN})\text{-APB/ODPA}$ and PVDF as a function of temperature. Reliable measurements for the $(\beta\text{-CF}_3)\text{-APB/OPDA}$ sample were not obtained. Commercially obtained PVDF provided a standard for the g_{33} measurement. At room temperature, the calculated g_{33} coefficient of 0.302 Vm/N for PVDF is in good agreement with the literature value of 0.339 Vm/N [3].

From Figure 1 it can be seen that: (1) the piezoelectric responses of the polyimide samples increase as the temperature increases from 40°C to 80°C whereas the piezoelectric response of PVDF is constant over this temperature range, and; (2) the magnitude of g_{33} for the polyimides at 80°C is more than an order of magnitude greater than the g_{33} constant for PVDF. The first observation can be understood based on fact that PVDF is a semicrystalline ferroelectric polymer operating above its T_g , whereas, the polyimides are amorphous polymers operating below their T_g 's (See Table 2). The second observation is believed to result from the presence of highly polar trifluoro and cyano groups pendant to the polyimide backbone.

The T_g of PVDF is -50°C [4]. At temperatures ranging from 20°C to 80°C , the mobility in PVDF is already maximized and thus there is no change in the piezoelectric response [5]. On the other hand, the T_g 's for the polyimides range from 170°C to 220°C . For the measurement temperature range, dipole motion increases with temperature in the polyimides with a corresponding dramatic increase in piezoelectric response. However, the rotational barrier of the pendant dipoles is still too high to promote dipole randomization. As the temperature approaches the T_g , the piezoelectric response of the polyimides level off. The $(\alpha,\delta\text{-CF}_3)\text{-APB/OPDA}$ sample electrically shorted prior to its plateau, but it appears that the g_{33} constant for this sample would have leveled off at around 11 Vm/N for temperatures above 90°C .

The relative magnitudes of the g_{33} constants for PVDF and the polyimides are predicted by Makowski's semi-empirical molecular orbital calculations [6]. As shown in Figure 2, Makowski showed that the predicted dipole moment for a model polyimide moiety which contains pendant polar substituents such as cyano and trifluoro groups is almost an order of magnitude greater than that of PVDF. In Figure 1, the piezoelectric response of the polyimides is an order of magnitude greater than PVDF at 80°C . Makowski also predicted that a cyano-containing model polyimide compound has a larger dipole moment than a trifluoro-containing model polyimide. As seen in Figure 1, the largest overall piezoelectric response was observed for the cyano-containing polyimide. The lower response of the polyimide containing three trifluoro groups relative to the polyimide which contains two trifluoro groups is believed to be the result of steric effects which limit polarization and the resulting piezoelectric response.

Table 2. Comparison of piezoelectric properties of some polymeric materials.

Material	T (°C)	T _g (°C)	T-T _g (°C)	ε	g _{ij} (Vm/N)	d _{ij} (pC/N)
PVDF ^a	25	-50	+75	12	0.339	33
Nylon-11 ^b	25	68	-43	3.7	0.217	7.1
Polyimide ^c (β-CN)- APB/ODPA	25	220	-195	3.9	0.188	6.5
Polyimide ^c (β-CN)- APB/ODPA	90	220	-130	3.7	13.57	444

a. Piezoelectric constants are g₃₃ and d₃₃ from [3].

b. Piezoelectric constants are g₃₁ and d₃₁ from [4].

c. Piezoelectric constants are g₃₃ measured in this work and d₃₃ calculated by
 $d_{ij} = \epsilon \epsilon_0 g_{ij}$ [7].

CONCLUSIONS

A strong piezoelectric response was observed for a series of polyimide films with pendant, polar trifluoro and cyano groups. Measurement of the piezoelectric response indicated that the g₃₃ coefficient for these polyimides increased dramatically with increasing temperature. These novel piezoelectric polymers exhibited polarization stability at temperatures in excess of 100°C.

REFERENCES

1. H. Kawai, *Jpn. J. Appl. Phys.*, **8**, 975 (1969).
2. G.M. Sessler, *J. Acoust. Soc. Am.*, **70** (6), 1596-1608 (1981).
3. Piezo Film Sensors Technical Manual, AMP, Inc., (1993).
4. Y. Takase, J.W. Lee, J.I. Scheinbeim, and B.A. Newman, *Macromolecules*, **24**, 6644 (1991).
5. G. Thomas Davis, in *Polymers for Electronic and Photonic Applications*, edited by C.P. Wong (Academic Press, Inc., Boston, 1993) pp. 435-465.
6. M. P. Makowski, NASA Technical Memorandum, (1991).
7. G. Thomas Davis, in *The Applications of Ferroelectric Polymers*, edited by T. Wang, J. Herbert, and A. Glass (Blackie, London, 1988) pp. 37-65.

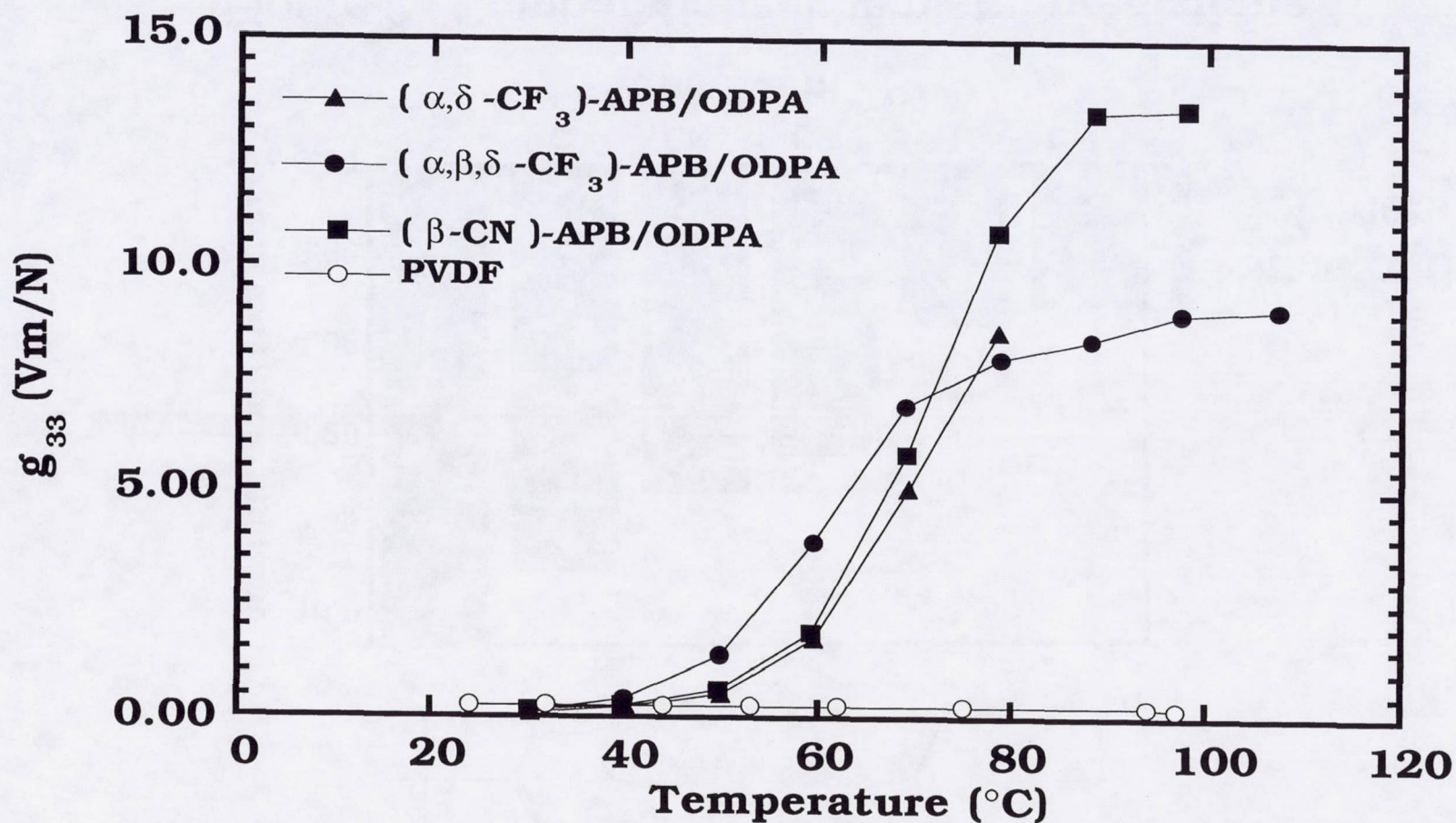


Figure 1. Temperature dependence of the piezoelectric constant for polyimides and PVDF.

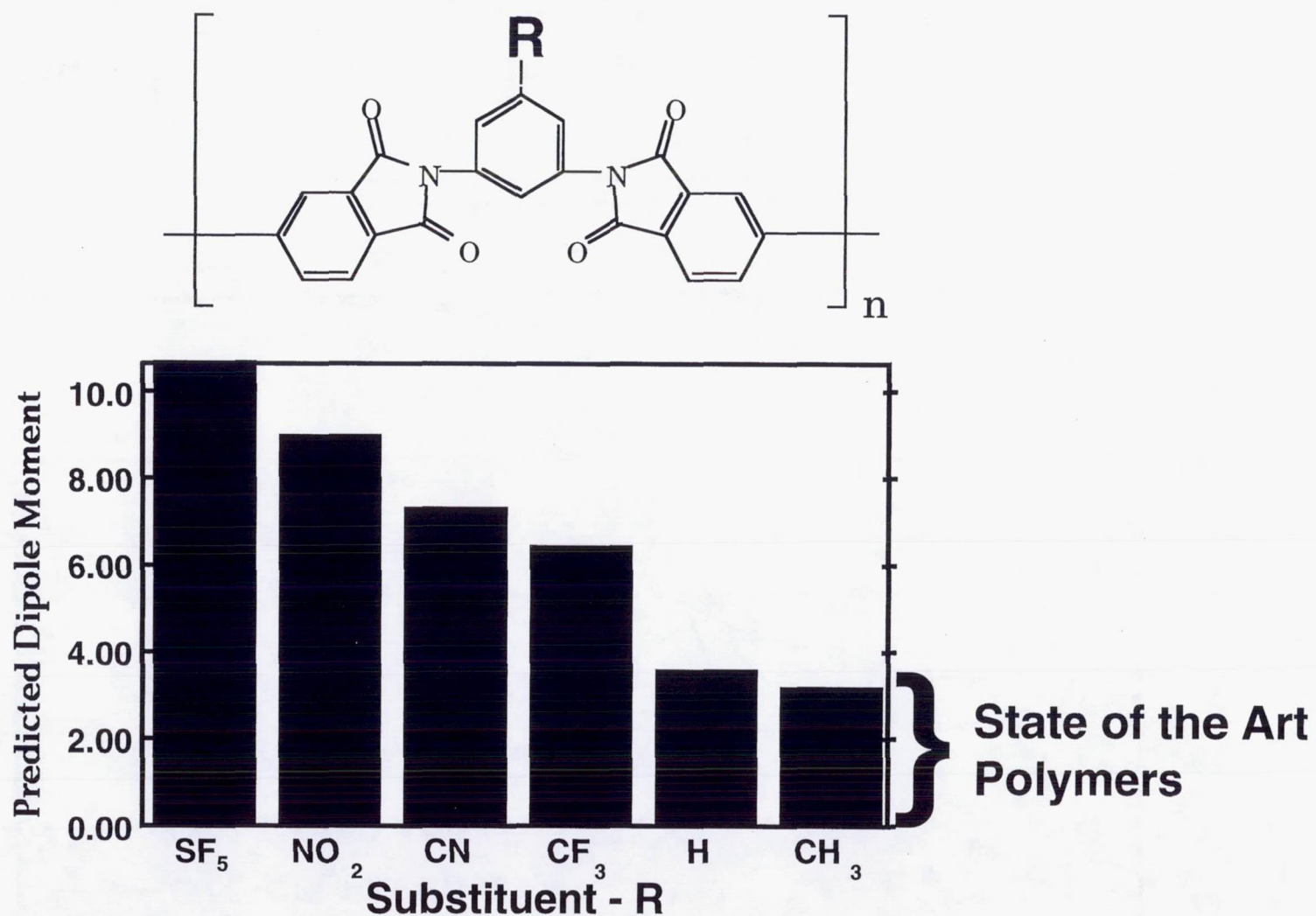


Figure 2. Computational chemistry predictions of dipole moments for a polyimide moiety with polar pendant groups [6].

540-33

AB50NLY

61524

235127

1P.

Development of Torsional and Linear Piezoelectrically Driven Motors

Khanh Duong, David Newton and Ephraim Garcia
Smart Structures Laboratory
Department of Mechanical Engineering
Vanderbilt University
Nashville, TN 37235

The development of rotary and linear inchworm-motors using piezoelectric actuators is presented. The motors' design has the advantage of a macro and micro stepper motor with high load and speed. The torsional design is capable of fast angular positioning with micro level accuracy. Additionally, the rotary motor, as designed, can be used a clutch/brake mechanism. Constructed prototype motors of both types along with their characteristics are presented. The torsional motor consists of a torsional section that provides angular displacement and torque, and two alternating clamping sections which provide the holding force. The motor relies on the principal piezoelectric coupling coefficient (d_{33}) with no torsional elements, increasing its torque capability. The linear motor consists of a longitudinal vibrator that provides displacement and load, and two alternating clamping sections which provide the holding force. This design eliminates bending moment, tension and shear applied to the actuator elements, increase its load capability and life. Innovative flexure designs have been introduced for both motor types. Critical issues that affect the design and performance of the motors are explored and discussed. Experiments are performed demonstrating the motor prototypes based on the aforementioned design considerations.

341-27
ABS ONLY
61528
235128
17.

**Effect of Temperature and Deformation Rate on the Tensile
Mechanical Properties of Polyimide Films**

Dr. Samir F. Moghazy, Kevin C. McNair
Physics Department
Clark Atlanta University
Atlanta, GA 30314, USA

In order to study the structure-property relationships of different processed oriented polyimide films, the mechanical properties will be identified by using tensile tester Instron 4505 and structural information such as the 3-dimensional birefringence molecular symmetry axis and 3-dimensional refractive indices will be determined by using wave guide coupling techniques. The monoaxial drawing techniques utilized in this research are very useful for improving the tensile mechanical properties of aromatic polyimide films. In order to obtain high modulus/high strength polyimide films the following two techniques have been employed, cold drawing in which polyimide films are drawn at room temperature at different cross head speeds and hot drawing in which polyimide films are drawn at different temperatures and cross head speeds. In the hot drawing process the polyimide films are drawn at different temperatures until the glass transition temperature (T_g) is reached by using the environmental chamber. All of the mechanical and optical property parameters will be identified for each sample processed by both cold and hot drawing techniques.

Electromechanical Materials for Cryogenic Use

Peter Leidinger*, Steven M. Pilgrim**

Presented at the 4th Annual Advances in Smart materials for Aerospace Applications Workshop at NASA Langley Research Center, May 1995.

Abstract

Electromechanical materials can be used in smart sensor and actuator devices. Yet none performing at low temperatures are available. To meet this need, $\text{Pb}((\text{MgNi})_{1/3}\text{Ta}_{2/3})\text{O}_3$ was synthesized as an electrostrictive ceramic for applications in cryogenic environments. Employing the columbite precursor route, samples with 0% to 100% Ni substitution for Mg were prepared, but only samples with Ni-substitutions $\leq 20\%$ yielded primarily the desired perovskite phase. For these compositions the temperature of highest permittivity decreased linearly with increasing Ni content to yield a minimum value of -124°C for 20% Ni-substitution. This composition showed good relaxor dielectric behavior with a maximum relative permittivity of 5890 at 1 kHz. Additionally, in samples with excess MgO, the magnitude of permittivity doubled. In this effort, $\text{Pb}((\text{MgNi})_{1/3}\text{Ta}_{2/3})\text{O}_3$ (PMNiTa) was fabricated to lower its transition temperature by substituting Ni for Mg successively.

I. Overview and Experimental

Electric polarization can cause a material to develop strain: by electrostriction and perhaps piezoelectricity. Piezoelectricity is limited to certain crystal types, but electrostriction is present in all materials [1, 2]. Electrostrictive strain s depends on the electric field (E):

$$s = Q (k' - 1)^2 (\epsilon_0 E)^2 \quad (1)$$

where permittivity of vacuum is ϵ_0 and relative permittivity is k' . Eqn. 1 shows $Q (k' - 1)^2$ is a useful figure of merit and that high permittivity is a strong indicator of a good electrostrictor. Although there are no cryogenic electrostrictors, Bokov and Myl'nikova reported a low transition temperature in single crystal $\text{Pb}(\text{Ni}_{1/3}\text{Ta}_{2/3})\text{O}_3$ [3]. This is an analog to PMN and should be a good electrostrictor.

PMNiTa was processed by a conventional columbite precursor route [4, 5], to reduce pyrochlore formation in favor of perovskite. Seven different compositions of $\text{Pb}((\text{Mg}_{1-x}\text{Ni}_x)_{1/3}\text{Ta}_{2/3})\text{O}_3$ were prepared: $x=0.0, 0.1, 0.2, 0.3, 0.5$, and 1.0 . One batch with $x=0.0$ had 5 weight percent of MgO added. Specific details of the process route are included in reference 4. A figure of merit for the perovskite yield was calculated from the intensity ratio highest intensity in the pattern of pyrochlore or perovskite (111 and 100 peaks) respectively. After electroding with fire on gold paste, capacitance and dielectric loss were measured as a function of temperature. From these data, relative permittivities, dielectric loss (D), and the diffuseness (δ), were calculated [4], [6], [7].

* Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

**New York State College of Ceramics at Alfred University, Alfred, New York 14802

III. Discussion and Conclusions

Samples with $x > 0.2$ consisted of pure pyrochlore according to x-ray diffraction. Compositions $x=0.0$ and $x=0.1$ both had 75% perovskite and composition $x=0.2$ had the maximum of 94% perovskite. The MgO excess sample had 82% perovskite. Results of the dielectric measurements are summarized in Table 1. Dielectric results are presented in the following figures.

Presently, the biggest problem in the fabrication of PMNiTa is the formation of a deleterious pyrochlore phase. Excess MgO seems to increase the perovskite yield; a fact previously noted for other relaxor ferroelectrics [8]. It is evident that Ni lowers the material's temperature of highest permittivity by about 10°C per 10% Ni substitution for Mg. Extrapolation of the 1 kHz curve results in a temperature of highest permittivity of -200°C. The obstacles to realizing this are strictly processing related.

Obviously, future work on PMNiTa should focus on processing. This initial work started with the conventional columbite precursor route. Now one might optimize processing parameters like calcination or firing temperature. A parallel step should be to consider effects at the grain boundaries when perovskite formation is unsuccessful -- perhaps incorporating segregation preventing additives. Further on considerations of other processing routes like sol-gel processing or hydrothermal synthesis might become necessary.

Nonetheless, a cryogenic electrostrictive material would enable a large variety of applications and close a gap among current "smarties". It could be put into action in environments requiring low temperatures due to the use of superconducting materials (e.g. as micropositioner in the hard drive of the superconducting computer), in space applications like active vibration dampers for satellites, or in proportional valves and transducers for cryogenic tankage.

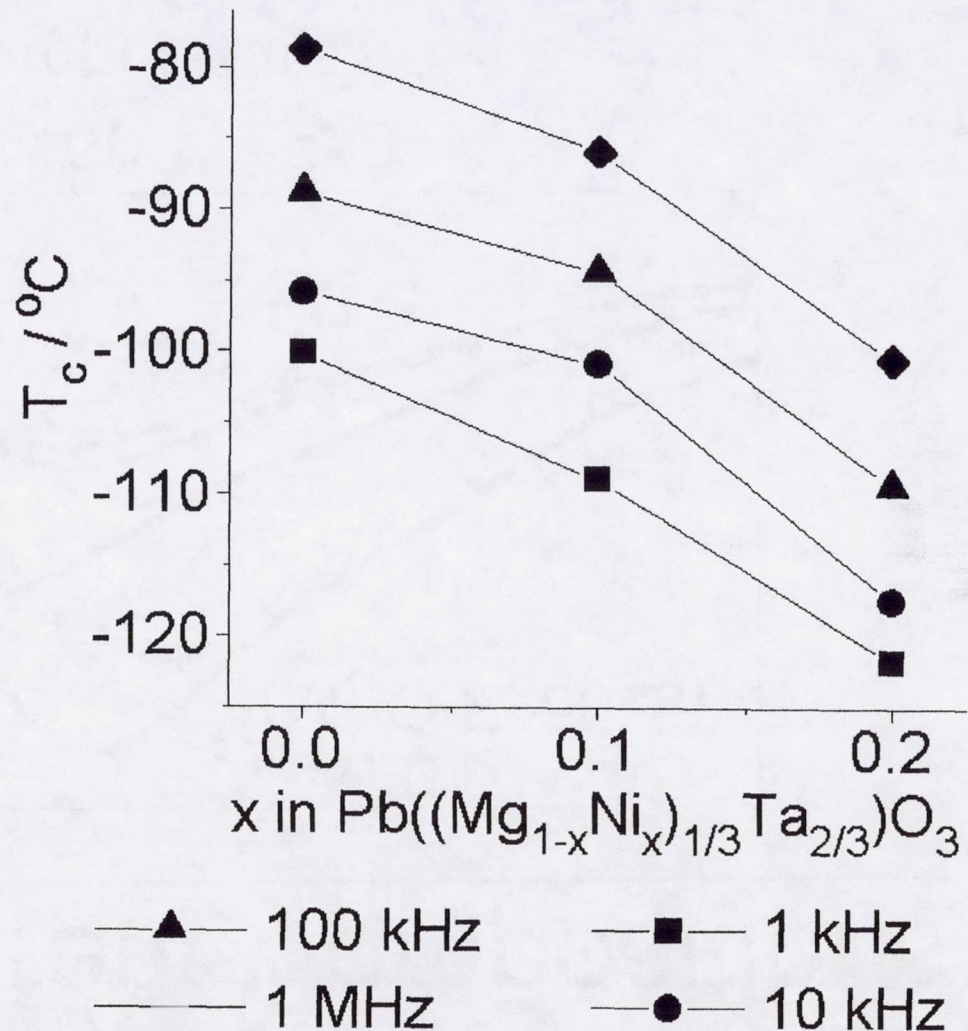
IV. References

- [1] L. E. Cross, "Relaxor Ferroelectrics", *Ferroelectrics*, 76 241-67 (1987).
- [2] V. Sundar, R. E. Newnham, "Electrostriction and Polarization", *Ferroelectrics*, 135 431-46 (1992).
- [3] V. A. Bokov, I. E. Myl'nikova, "Ferroelectric Properties of Monocrystalline Perovskites", *Sov. Phys. Solid State*, 2 2428 (1961).
- [4] P. Leidinger and S. M. Pilgrim, "Fabrication and Dielectric Properties of Lead Magnesium Nickel-Tantalates", submitted to *J. Amer. Ceram. Soc.*, (May 1994).
- [5] S. L. Swartz, T. L. Shrout, "Fabrication of Perovskite Lead Magnesium Niobate", *Mater. Res. Bull.*, 17 1245-1250 (1982).
- [6] S. M. Pilgrim, A. E. Sutherland, S. R. Winzer, "Diffuseness as a Useful Parameter for Relaxor Ceramics", *J. Amer. Ceram. Soc.*, 73 [10] 3122-25 (1990).
- [7] G. A. Smolenski, "Physical Phenomena in Ferroelectrics with Diffused Phase Transition", *Journal of the Physical Society of Japan*, 28 Supplement 26-37 (1970).
- [8] A. E. Sutherland, S. M. Pilgrim, A. E. Bailey, S. R. Winzer, "Dielectric Aging of Doped PMN-PT Ceramics", in *Ceramic Transactions Vol. 15*, American Ceramic Society: Westerville, OH, 1990, pp. 105-27.

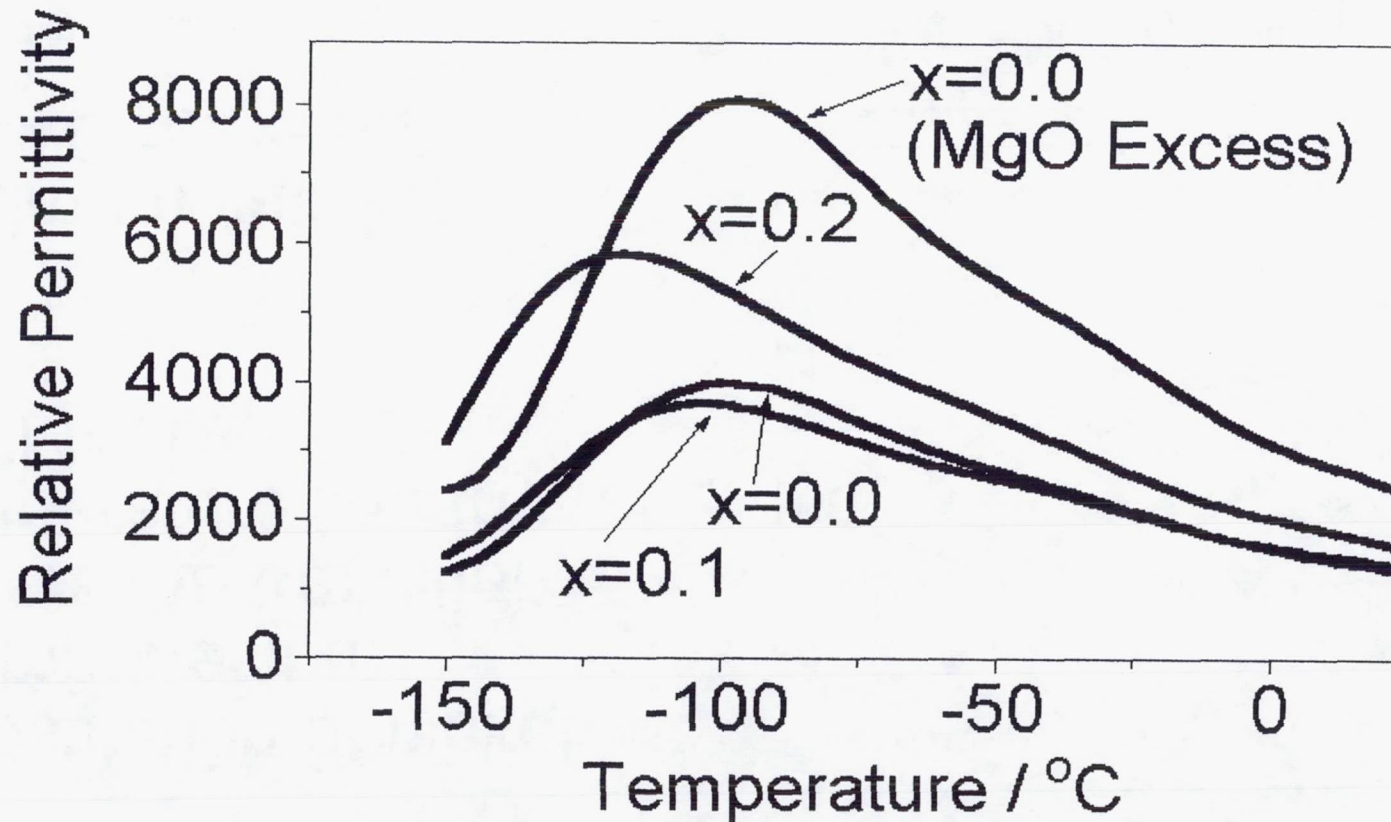
Transition Temperature versus Composition

Substitution of nickel
for magnesium
lowers the transition
temperature linearly
in PMNiTa.

Minimum value is
-124°C for $x=0.2$ at
1 kHz.



k' vs T for Different Compositions



- Increase in Ni substitution (x) causes decrease in T_c down to -124°C for $x=0.2$.
- Excess MgO doubles k'_{max} and does not change T_c .

Dielectric Data

Frequency

1 kHz				10 kHz			100 kHz			1 MHz			$\Delta T_c / ^\circ\text{C}$
x	k'_{max}	$T_c / ^\circ\text{C}$	$d / ^\circ\text{C}$	k'_{max}	$T_c / ^\circ\text{C}$	$d / ^\circ\text{C}$	k'_{max}	$T_c / ^\circ\text{C}$	$d / ^\circ\text{C}$	k'_{max}	$T_c / ^\circ\text{C}$	$d / ^\circ\text{C}$	
0.0	4030	-102	63	3860	-98	61	3670	-91	59	3410	-82	56	21
0.1	3960	-110	74	3570	-101	71	3420	-94	68	3220	-86	65	24
0.2	5890	-124	68	5690	-118	66	5440	-108	62	5130	-101	58	23
MgO excess													
0.0	8180	-101	58	7810	-94	57	7380	-87	56	6840	-79	54	22

x: Amount of Ni substitution for Mg

k'_{max} : Maximum relative permittivity

T_c : Transition temperature

d: Diffusivity

$\Delta T_c = T_c(1 \text{ MHz}) - T_c(1 \text{ kHz})$

Page intentionally left blank

543-27
61533
235130

5P.

FIRST CYCLE HETEROGENEOUS DEFORMATION BEHAVIOR AND CYCLIC
SHAKEDOWN PHENOMENA OF NITINOL NEAR A_f TEMPERATURES

H. N. Jones
CODE 6321
NAVAL RESEARCH LABORATORY

Abstract - Experimental observations on the cyclic behavior of a NiTi alloy (Nitinol) at temperatures in the neighborhood of the A_f (austenite finish) temperature are presented. The strongly heterogeneous nature of the deformation behavior of this material at temperatures within this regime during the first cycle is examined with emphasis placed on the difficulties that the existence of such phenomena pose on the formulation of realistic constitutive relations. It is further demonstrated that this heterogeneity of deformation persists on subsequent cycles with the result that the hysteretic cyclic behavior of these alloys can exhibit a point to point variation in an otherwise uniform geometry. The experimental observations on the deformation behavior of this alloy show that it is strongly dependent on temperature and prior deformation history of the sample, thus resulting in an almost intractable problem with respect to capturing an adequate constitutive description from either experiment or modeling.

Discussion - When formulating constitutive descriptions of the mechanical behavior of shape memory alloys it is often assumed that, for a given state of stress and temperature, a uniquely determined strain response is had [1]. If, however, an otherwise uniform geometry, such as a polycrystalline wire, is instrumented at more than one point it is observed that at temperatures near A_f (austenite finish) the stress-strain behavior is not the same despite the fact that the stress is nearly the same at both points. An example of this heterogeneous deformation behavior is shown on Fig. 1 where the room temperature (26 C) first cycle stress-strain curves of two points of a 2.54 mm diameter Nitinol wire with an A_f of 24 C are superimposed. It should also be noted that these stress-strain curves cannot be conducted under isothermal conditions at reasonable strain rates as considerable heat is released by the stress induced austenite to martensite phase transformation as shown on Fig. 2. This temperature history is a function of both the imposed strain rate and the local strain rate response, with higher imposed strain rates producing higher peak temperatures.

Another problem presenting itself to the formulation of a constitutive description is the change in stress-strain behavior with cycle count as illustrated in Fig. 3. As a consequence of this "shakedown" phenomena the hysteretic energy dissipation tends to a minimum steady state value as cycle count increases. Once a stable cyclic loop is achieved the material becomes mechanically reversible, but remains thermodynamically irreversible, since there persists a stress-strain hysteresis which indicates that work is being dissipated as heat. The evolution of the material to a mechanically reversible state is not the same at every point, as demonstrated by the differences in dissipated energy for identical stress excursions, and there are some residual differences even at high cycle counts.

The shape of a cyclic loop, once a mechanically reversible state is achieved, is a function of the strain rate as this influences the peak temperatures attained at the peak stress end of the cycle. Additionally, if the cyclic frequency is increased the average temperature starts to increase as result of the dissipative processes in the material which reduces the area within the cyclic loop, but soon reaches a steady state. This is primarily a function of the rate at which heat is lost to the surroundings. There is a coupling between the cyclic frequency, the rate at which heat can be extracted from the wire, and the energy dissipated per cycle.

As was demonstrated above, and as has been observed by others, the deformation behavior of a shape memory alloy is a function not only of temperature, but is also affected by the strain rate and the number of cycles [2]. In other words, there are both rate effects and thermomechanical history effects that strongly govern the stress-strain behavior of these materials. Most attempts at formulating a constitutive relationship, however, have a form given by:

$$\sigma = \sigma(\epsilon, \xi, T) \quad (1)$$

where ϵ is the strain, ξ is the volume fraction of martensite, and T is the temperature [3]. While rate effects and history effects obviously cannot be described by such an approach, once a stable cyclic loop is achieved constitutive parameters could then be derived which, however, would be of limited applicability.

To describe the evolution of the material to a stable stress-strain behavior with increasing cycle count requires the realization that not all work done on the material is stored as "pseudoelastic" strain energy or dissipated as heat, some of it is partitioned off into structural modifications that modify its mechanical response, such as dislocation structures and stabilized martensite. The energy balance equation would then need to be modified by the addition of a term to show that some work is stored as these structural modifications. Then there is, of course, the observation that there is a lack of uniqueness in the stress-strain behavior of this material under some circumstances which can persist for a number of cycles. It is felt, based on the observed complexity in the mechanical behavior exhibited by these materials, that the development of a constitutive relationship will be restricted to special cases where a stable loop has been achieved, as a description that captures all effects may be an intractable problem.

References:

1. K. Tanaka, S. Shigenori and Y. Sato, *International Journal of Plasticity*, Vol. 2, pp. 59-72, 1986.
2. J. S. Cory and J. L. McNichols, *J. Appl. Phys.*, Vol. 58 (9), pp. 3282-3294, 1985.
3. L. C. Brinson, *Journal of Intelligent Material Systems and Structures*, Vol. 4, pp. 229-242, 1993.

FIRST CYCLE STRESS-STRAIN CURVES

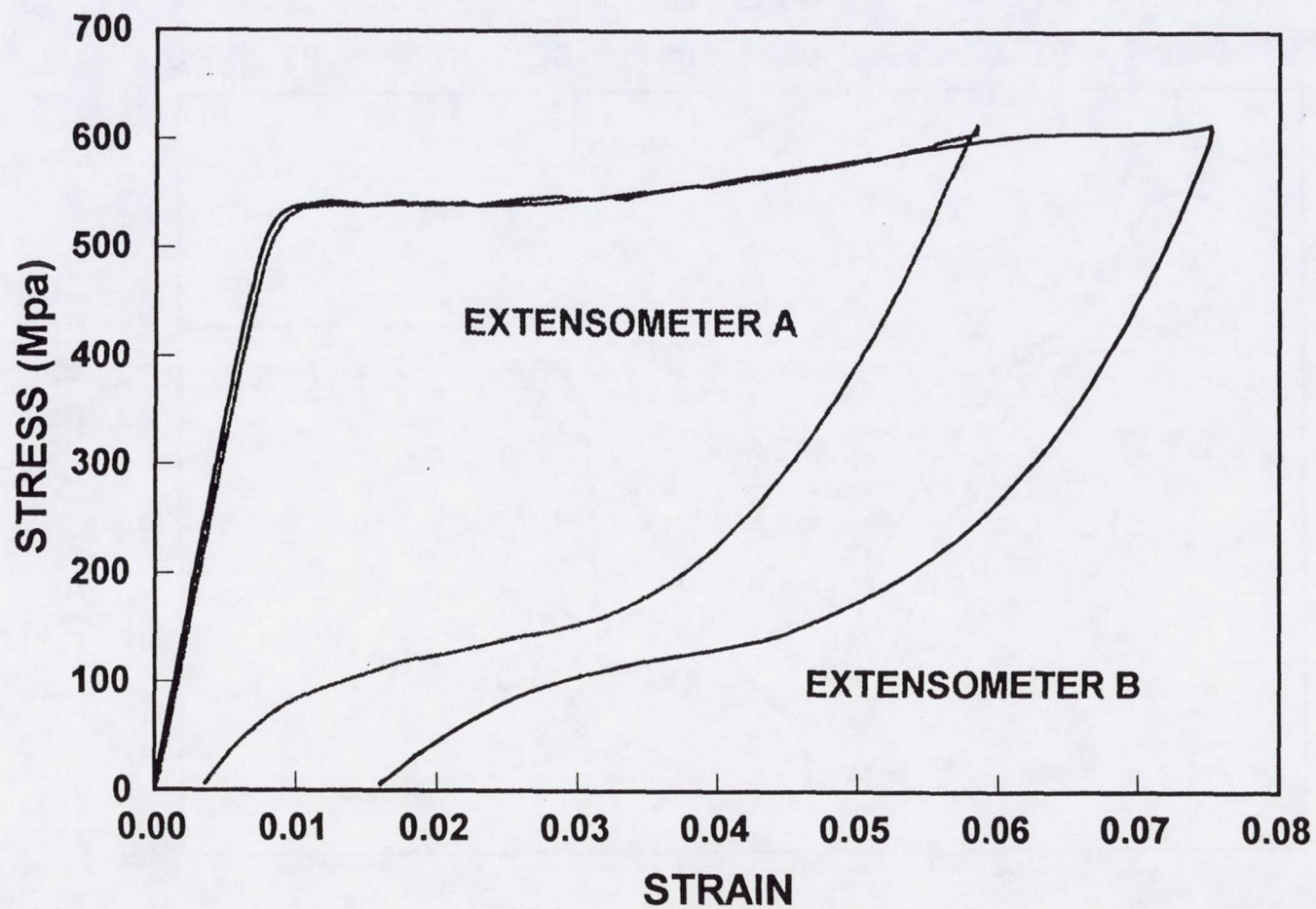


Figure 1

TEMPERATURE HISTORY

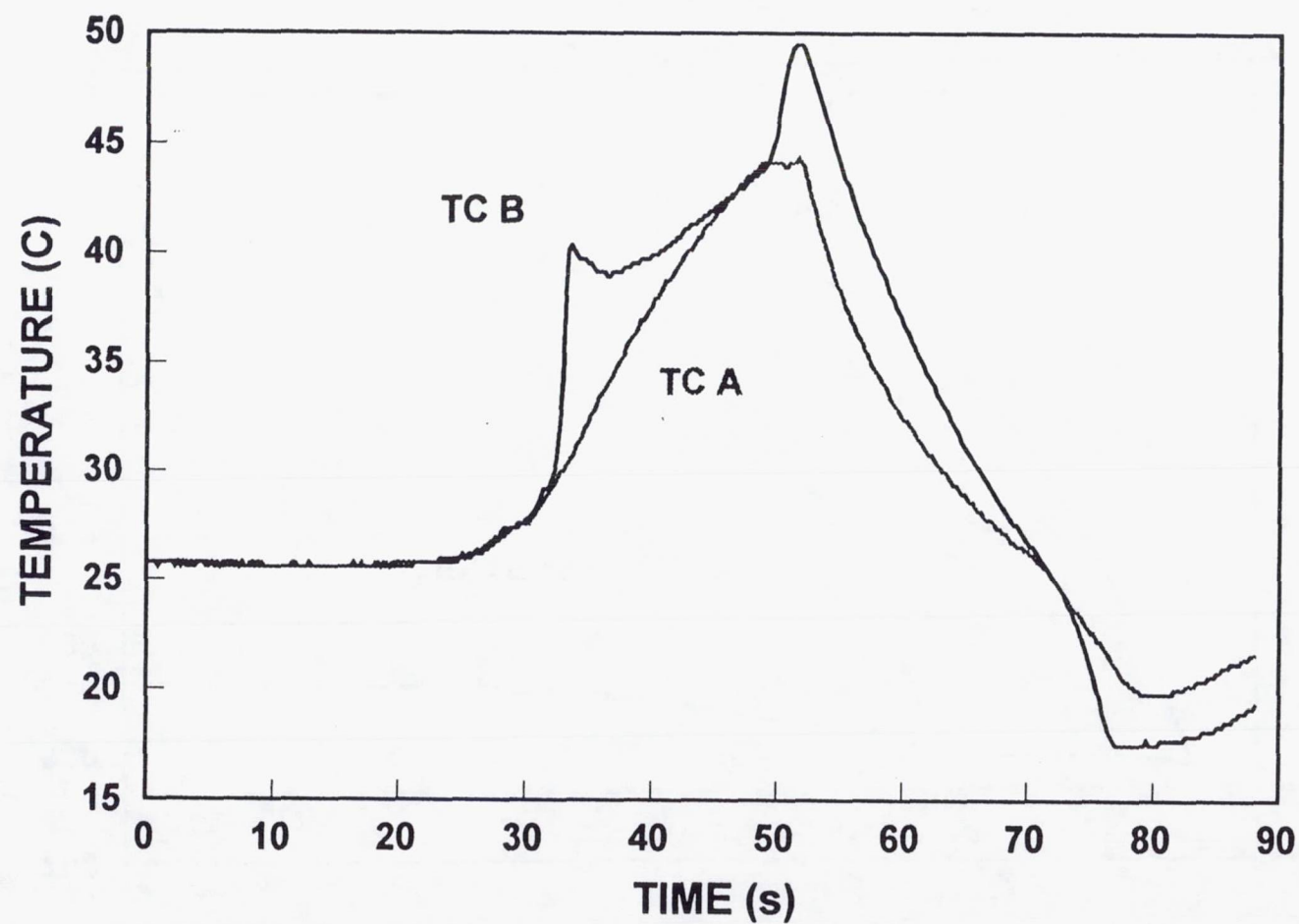


Figure 2

STRAIN B - STRESS

12 CYCLES ON NEW WIRE

CYF1, 18-JAN-95, 10:07:37, D/C=LSSD3T

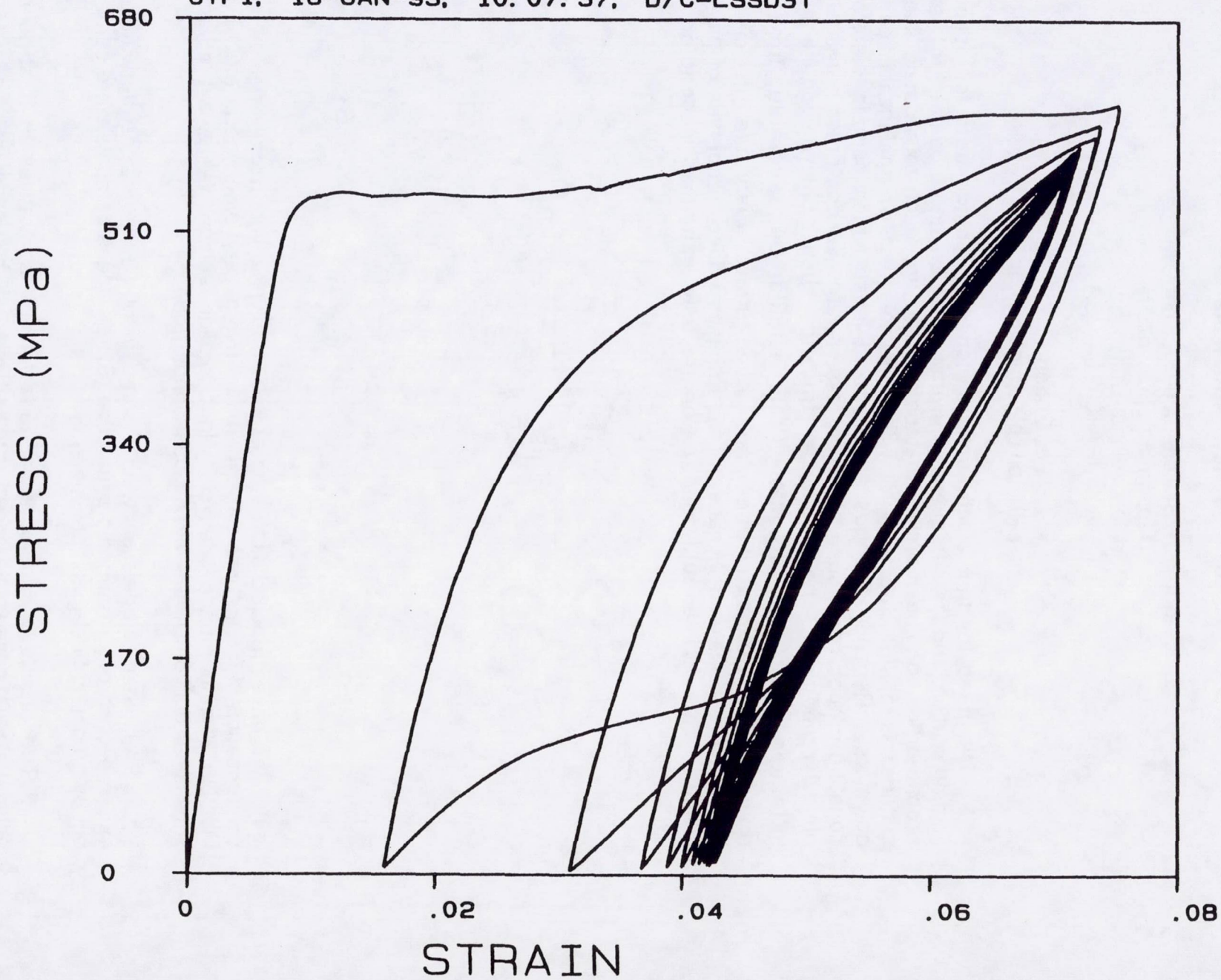


Figure 3

544-27
61536

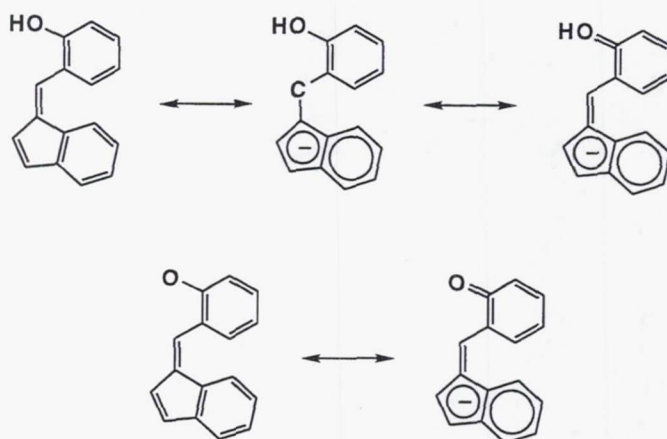
Incorporation of New Benzofulvene Derivatives Into Polymers to Give New NLO Materials

235131
1P.

Andrea D. Bowens, Xiu Bu, Eric A. Mintz
Department of Chemistry
Clark Atlanta University
Atlanta, GA 30314, USA

Yue Zhang
Laser Photonics Technology, Inc.

The need for fast electro-optic switches and modulators for optical communication, and laser frequency conversion has created a demand for new second-order non-linear optical materials. One approach to produce such materials is to align chromophores with large molecular hyperpolarizabilities in polymers. Recently fulvenes and benzofulvenes which contain electron donating groups have been shown to exhibit large second-order non-linear optical properties. The resonance structures shown below suggest that intramolecular charge transfer (ICT) should be favorable in ω -(hydroxyphenyl)benzofulvenes and even more favorable in ω - ω -(phenoxy)benzofulvenes because of the enhanced donor properties of the O group. This ICT should lead to enormously enhanced second-order hyperpolarizability.



We have prepared all three new ω -(Hydroxyphenyl)benzofulvenes by the condensation of indene with the appropriate hydroxyaryl aldehyde in MeOH or MeOH/H₂O under base catalysis. In a similar fashion we have prepared substituted benzofulvenes with multipal donor groups.

Preliminary studies show that some of our benzofulvene derivatives exhibit second order harmonic generation (SHG). Measurements were carried out by preparing host-guest polymers.

The results of our work on benzofulvene derivatives in host-guest polymers when covalently bonded in the polymer will be described.

54527
ABSONLY

Mechanical Response of Elastomers to Magnetic Fields 61538

B. C. Munoz and M. R. Jolly
Lord Corporation
Thomas Lord Research Center
405 Gregson Drive
Cary, NC 27511, USA

035132
1 p.

Elastomeric materials represent an important class of engineering materials, which are widely used to make components of structures, machinery, and devices for vibration and noise control. Elastomeric material possessing conductive or magnetic properties have been widely used in applications such as conductive and magnetic tapes, sensors, flexible permanent magnets, etc. Our interest in these materials has focussed on understanding and controlling the magnitude and directionality of their response to applied magnetic fields. The effect of magnetic fields on the mechanical properties of these materials has not been the subject of many published studies.

Our interest and expertise in controllable fluids have given us the foundation to make a transition to controllable elastomers. Controllable elastomers are materials that exhibit a change in mechanical properties upon application of an external stimuli, in this case a magnetic field. Controllable elastomers promise to have more functionality than conventional elastomers and therefore could share the broad industrial application base with conventional elastomers. As such, these materials represent an attractive class of smart materials, and may well be a link that brings the applications of modern control technologies, intelligent structures and smart materials to a very broad industrial area.

This presentation will cover our research work in the area of controllable elastomers at the Thomas Lord Research Center. More specifically, the presentation will discuss the control of mechanical properties and mathematical modeling of the new materials prepared in our laboratories along with experiments to achieve adaptive vibration control using the new materials.

546-27

ABSTRACT

Metal-Coated Optical Fibers for High Temperature Applications

Jason Zeakes, Kent Murphy and Richard Claus
Fiber & Electro-Optics Research Center

61542

235133

Jonathan Greene and Tuan Tran
Fiber & Sensor Technologists, Inc.

7P.

This poster will highlight on-going research at the Virginia Tech Fiber & Electro-Optics Research Center (FEORC) in the area of thin films on optical fibers. Topics will include the sputter deposition of metals and metal; alloys onto optical fiber and fiber optic sensors for innovative applications. Specific information will be available on thin film fiber optic hydrogen sensors, corrosion sensors, and metal-coated optical fiber for high temperature aerospace applications.

PIEZOELECTRIC ACTUATOR/SENSOR DESIGN FOR NONLINEAR PANEL FLUTTER SUPPRESSION

Jen-Kuang Huang and Chuh Mei

**School of Aerospace and Mechanical Engineering
Old Dominion University, Norfolk, Virginia**

**Fourth Workshop on Advances in Smart Materials
for Aerospace Applications**

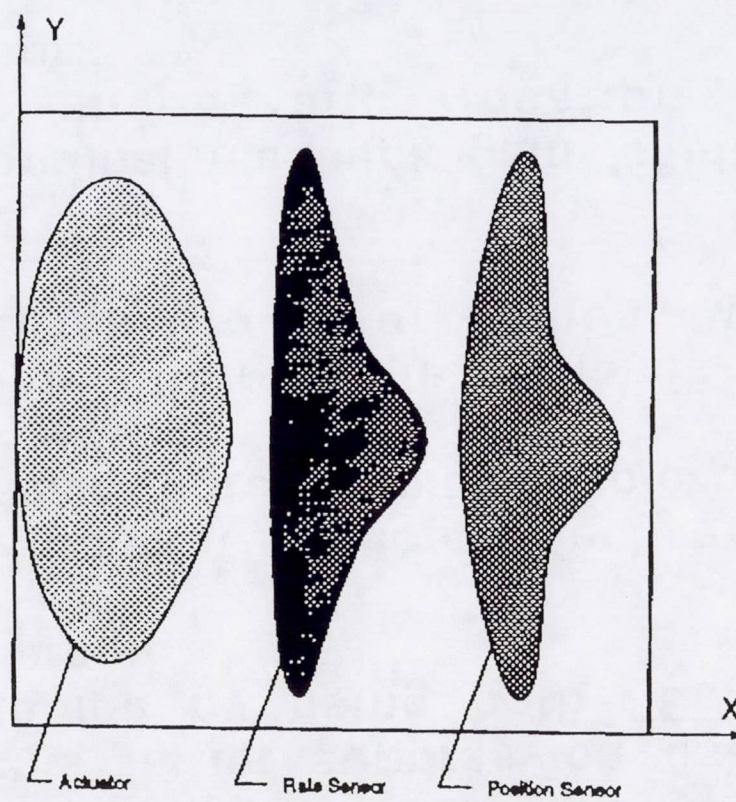
NASA Langley Research Center

May 4-5, 1995

GOALS

- To suppress nonlinear panel flutter motions by using piezoelectric materials as actuators/sensors.
- To design the optimal shape and location of piezoelectric actuator/sensor.
- To achieve the optimal control performance without using state estimators.

Layout of Piezoelectric Actuator and Two Sensors



CONCLUSIONS

- Nonlinear panel flutter suppression using smart materials has been studied by using both FEM and the classical continuum method.
- The bending moment is more effective than inplane force in active flutter suppression using piezoelectric actuation.
- The maximum suppressible dynamic pressure can be increased three to four times with the present configuration.
- The use of optimal feedback gain is effective in selection of optimal shape and location of piezoelectric actuator/sensor.
- The optimal actuator's location is near leading edge of the panel.
- The optimal control performance can be achieved by using shaped sensors with a simple rate-feedback controller.

547-27
61545
235134
4P.

REAL TIME DIGITAL CONTROL OF A MAGNETOSTRICTIVE ACTUATOR

Rick L. Zrostlik, David L. Hall, and Alison B. Flatau

Department of Aerospace Engineering and Engineering Mechanics
Iowa State University
Ames, Iowa 50011

The use of the magnetostrictive material Terfenol-D as a motion source in active vibration control (AVC) systems are being studied. Currently it is of limited use due to the nonlinear nature of the strain versus magnetization curve and the magnetic hysteresis in the Terfenol-D. One manifestation of these nonlinearities is waveform distortion in the output velocity of the transducer. For Terfenol-D to be used in ever greater numbers of AVC systems, these nonlinearities must be addressed. In this study the nonlinearities are treated as disturbances to a linear system. The acceleration output is used in simple analog and digital feedback control schemes to improve linearity of the transducer. In addition, the use of a Terfenol-D actuator in an AVC system is verified. Both analog and digital controllers are implemented and results compared.

A cantilever beam system is considered for AVC applications. The digital proportional controller uses a zero reference signal and the acceleration signal from the free end of the beam to produce an error signal. The acceleration signal was low passed to eliminate the controller from driving higher order modes in the beam. The error signal was converted back to an analog signal and amplified in a voltage control amplifier to drive the actuator. The fundamental frequency of the beam with no control is 110 Hz. With the digital controller implemented, classic dynamic absorber results are evident with two lobes at 90 Hz and 130 Hz and a fairly flat response at the previous peak of 110 Hz.

An analog controller was also used for comparison. While the analog proportional controller did reduce the fundamental mode of the beam as well as shift the frequency slightly, it did not reduce the acceleration peak as much as the digital controller. Figure 1 shows the acceleration for the system with analog, digital and no controllers implemented.

The second thrust of this presentation is the reduction of harmonic distortions. Initially an analog PD (proportional plus derivative) controller was used. The autospectral density of the output acceleration was plotted with and without the PD controller as figure 2. The 'x' data is without a controller used while the 'o' data uses a PD controller. Note the significant reductions in the 4000 Hz and 6000 Hz peaks.

The digital implementation of the harmonic distortion controller is slightly different than the analog counterpart. In this case the dynamics of the beam were included in the system. The time trace shows an improvement in the linearity of the system in figure 3.

Two conclusions can be reached from this work. One, the linearization of Terfenol-D transducers is possible with the use of feedback controllers, both digital and analog. Second, Terfenol-D is a viable motion source in active vibration control systems utilizing either analog or digital controllers.

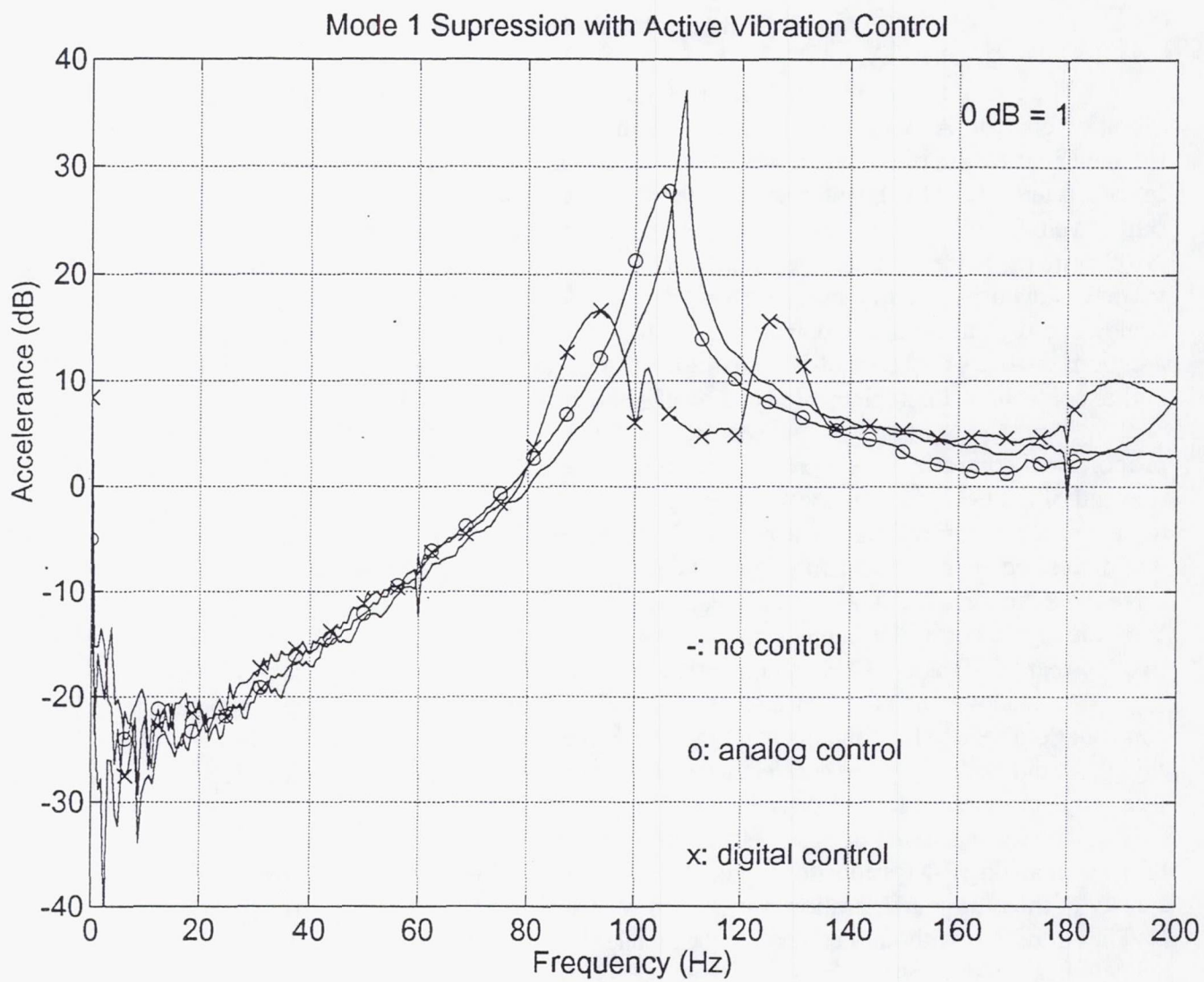


Figure 1: Beam accelerance due to impact by a hammer.

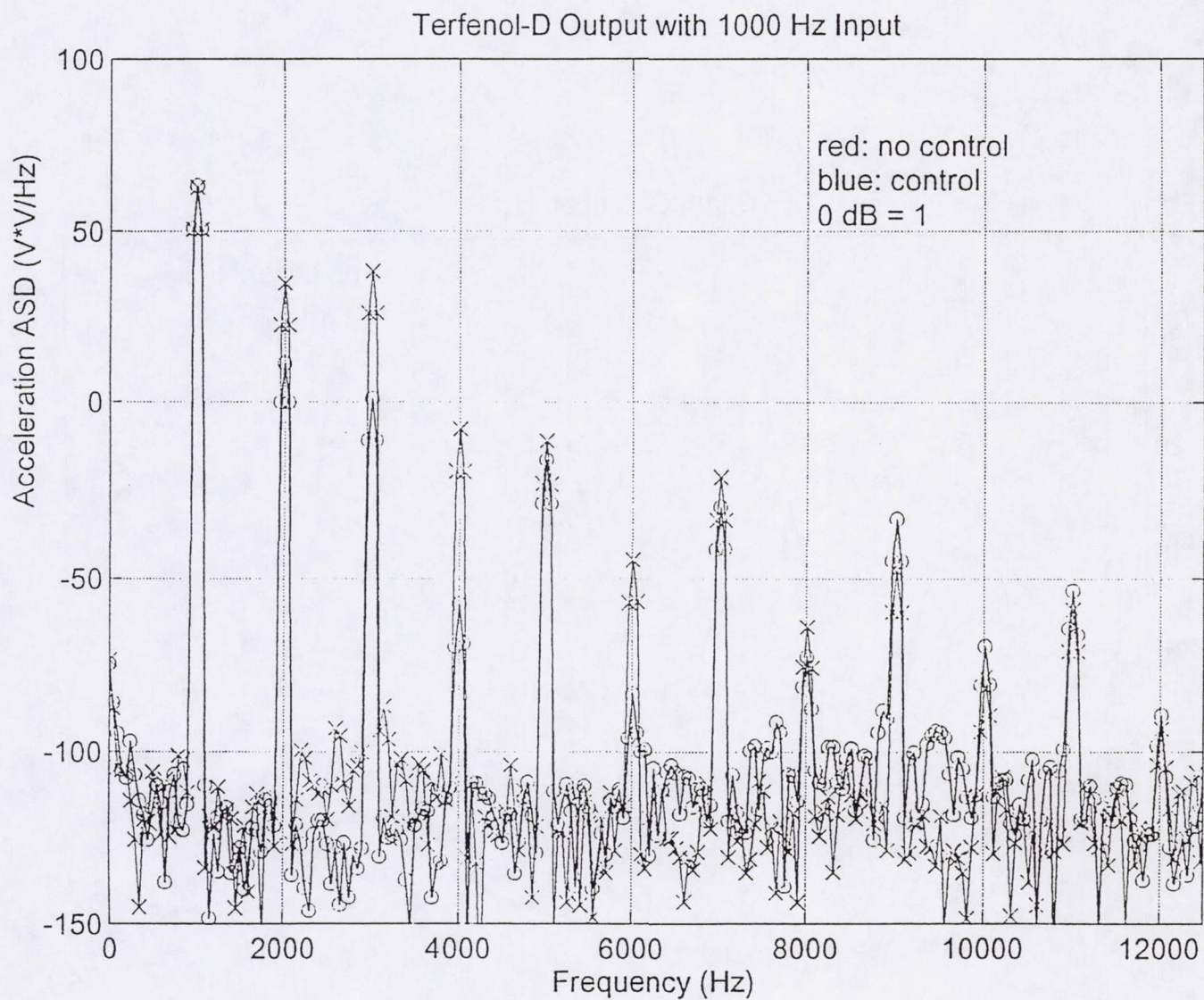


Figure 2: Autospectral density of output acceleration. Controller was analog PD.

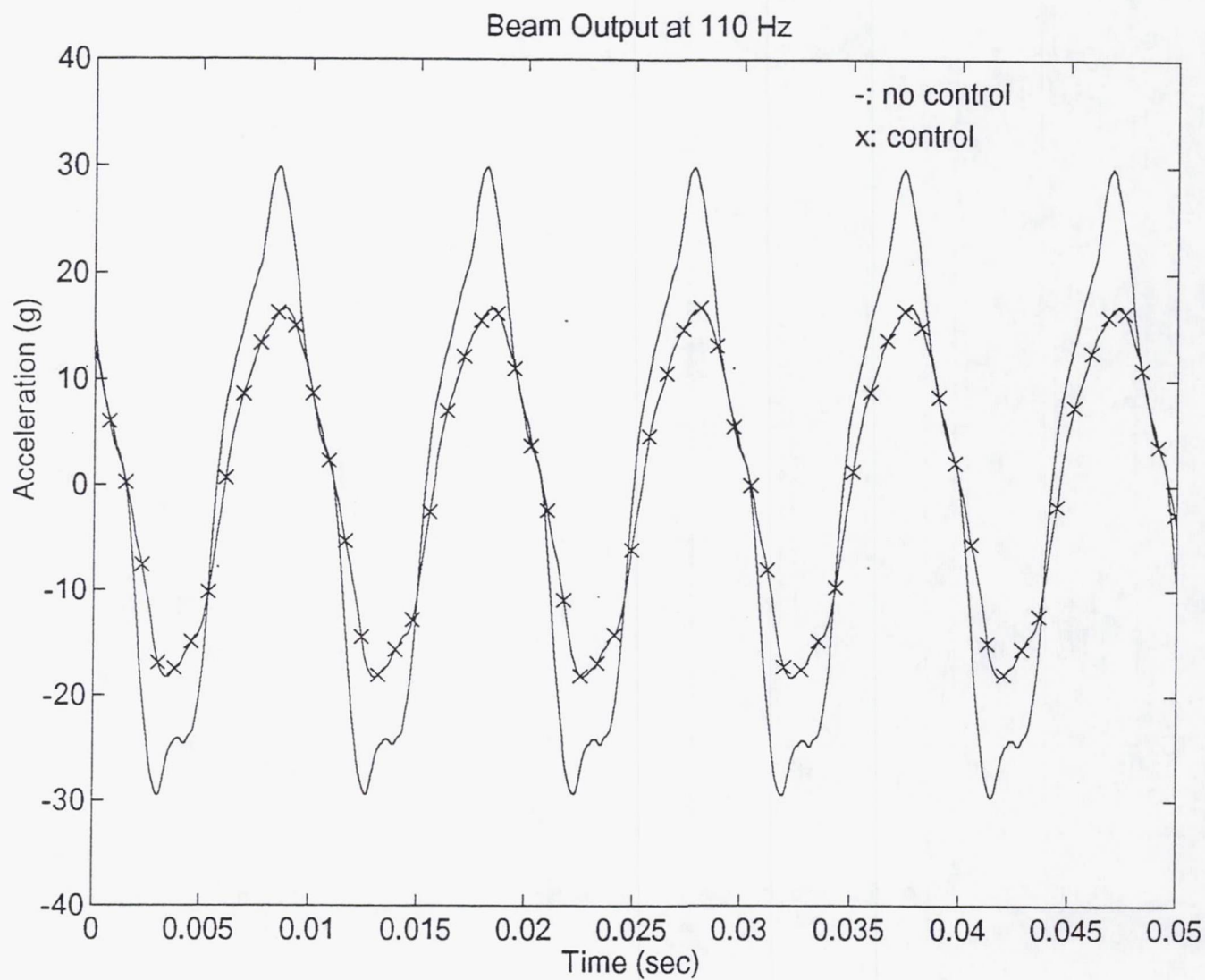


Figure 3: Acceleration of beam free end. Controller was proportional digital.

VGT Manipulator Arm

Garnett Horner
NASA Langley Research Center
Hampton, VA

4th Annual Workshop
Advances in Smart Materials for Aerospace Applications

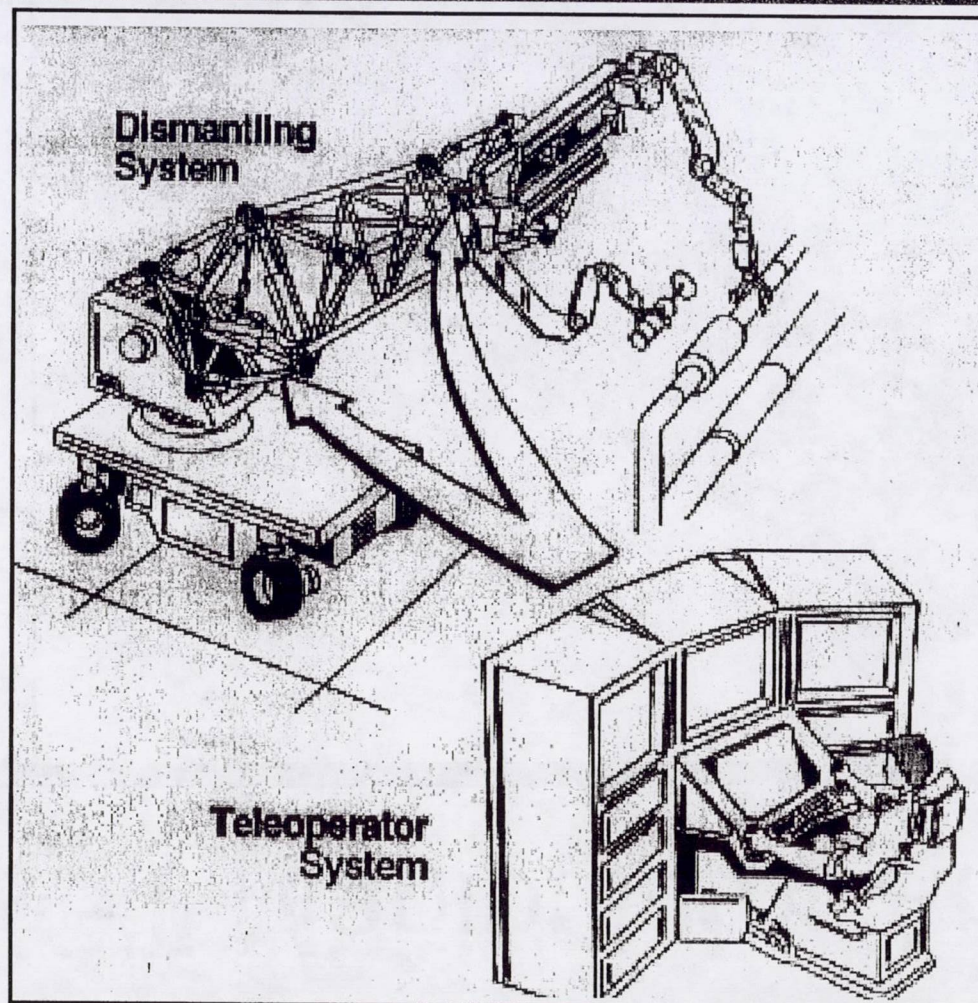
May 4,5 1995

548-27
61548
035135
6P.

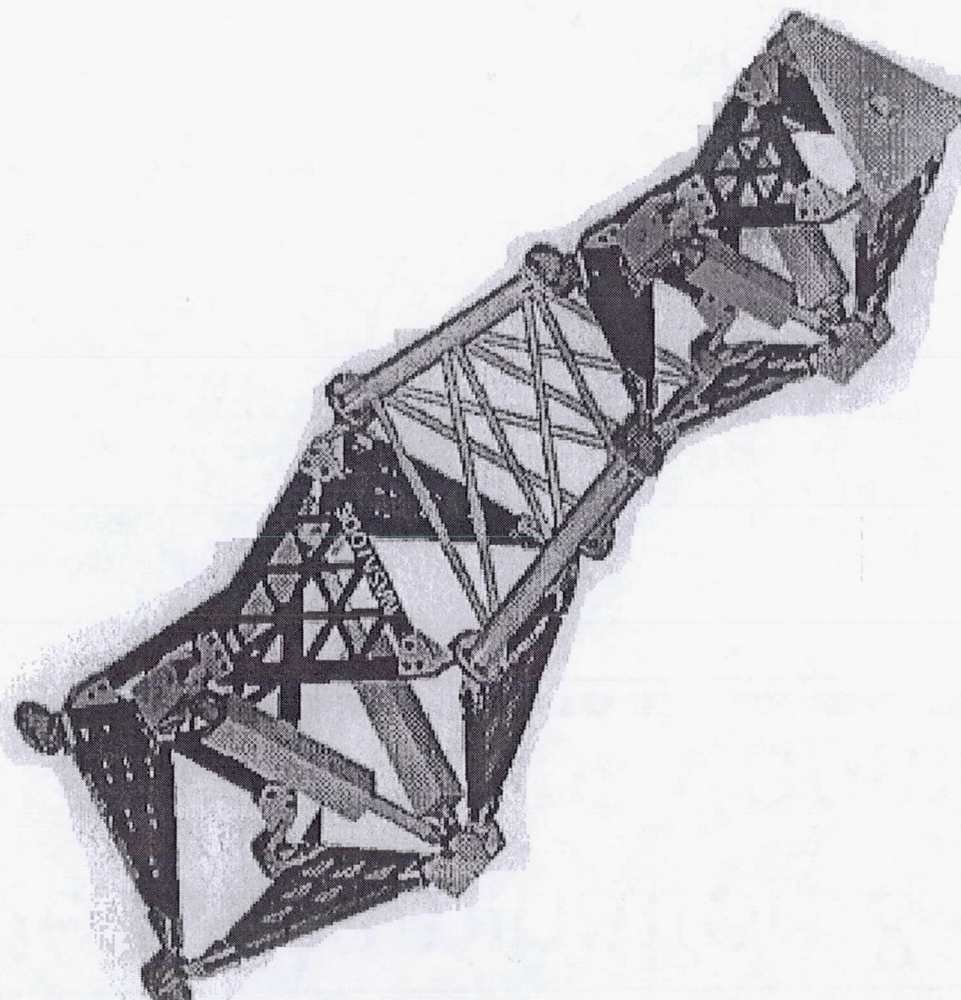
Variable Geometry Truss Manipulator Arm

- Joint program with Department of Energy's Decontamination and Dismantlement (D&D) Program
- Heavy lifting boom for a tele-operated D&D vehicle
- Supports a dual arm work module

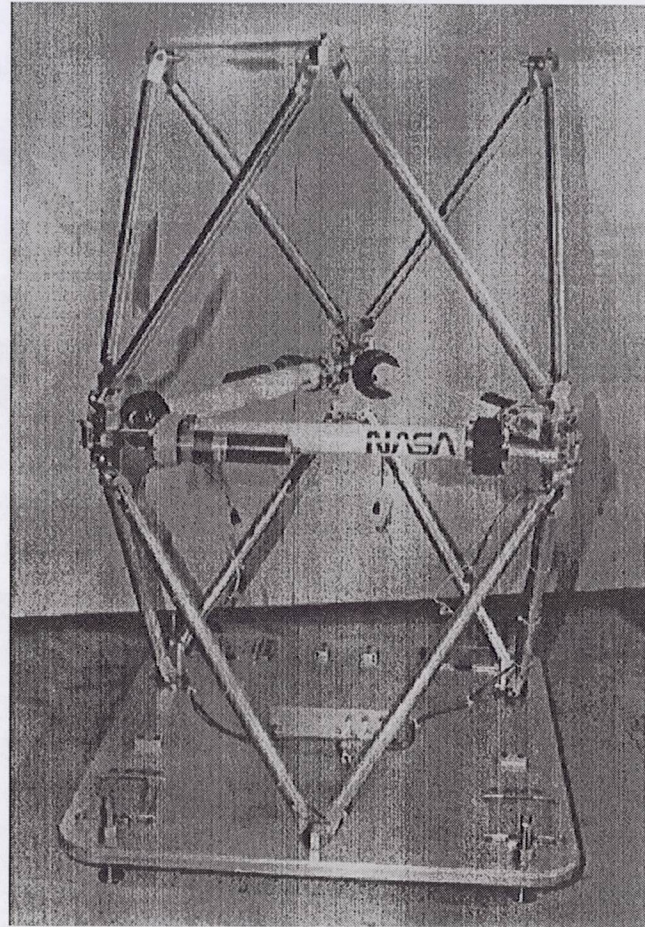
Decontamination & Dismantlement Vehicle



VGT Manipulator Arm



Variable Geometry Truss



Summary

- VGT Manipulator Arm is being designed with two VGT modules